PB-214 649

CHARACTERIZATION OF STREAM REAERATION CAPACITY

E. C. Tsivoglou, et al

Georgia Institute of Technology

Prepared for:

Environmental Protection Agency

October 1972

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

W73-05213

EPA-R3-72-012
October 1972

Ecological Research Series

PB 214 649

Characterization of Stream Reaeration Capacity

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

Office of Research and Monitoring
U.S. Environmental Protection Agency
Washington, D.C. 20460

324

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Monitoring, Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ECOLOGICAL RESEARCH series. This series describes research on the effects of pollution on humans, plant and animal species, and materials. Problems are assessed for their long- and short-term influences. Investigations include formation, transport, and pathway studies to determine the fate of pollutants and their effects. This work provides the technical basis for setting standards to minimize undesirable changes in living organisms in the aquatic, terrestrial and atmospheric environments.

SELECTED WATER RESOURCES ABSTRACTS

INPUT TRANSACTION FORM

1. Report No.

2.

3. Accession No.

W 73-05213

4. Title CHARACTERIZATION OF STREAM REAERATION CAPACITY,

5. Report Date

6.

8. Performing Organization Report No.

7. Author(s) Tsivoglou, E. C.; and Wallace, J. R.

10. Program EPA 16050 EDT

9. Organization

Georgia Institute of Technology, Atlanta, ~~Georgia~~

11. Contract/Grant No.

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes

Ecological Research Series Reports

Environmental Protection Agency, EPA-R3-72-012, October 1972, 317 p., ~~October, 1972~~, 71 fig., 28 tab., 24 ref., 4 append.

16. Abstract

Research was conducted to characterize stream reaeration capacity in terms of the stream hydraulic properties and to develop procedures for evaluating the effects of pollutants on reaeration. A gaseous tracer procedure was used in the field studies for measurement of reaeration. Not only have these studies incorporated a wide range of hydraulic features, but also, the range of BOD's and temperatures encountered was large. Tests of observed vs. predicted values of K_2 have shown that none of the available models is capable of providing dependable predictions of stream reaeration capacity, especially under highly turbulent flow conditions. A new model was derived that explains the reaeration capacity of a stream in terms of the rate of energy dissipation and furthermore, provides dependable predictions. The reaeration rate coefficient was shown to decrease with LAS and community wastes; remain constant with pure NTA; and increase with pure mineral oil. (Smith-Texas)

17a. Descriptors *Reaeration, *Streams, *Stream pollution, *Streamflow hydraulics, *Tracers, *Radicisotopes, *Dissolved oxygen, Biochemical oxygen demand, Temperatures, Mathematical models, Model studies, Turbulent flow, Turbulence, Mixing

17b. Identifiers

*Stream self-purification, *Flint river, *South river, *Patuxent river, *Jackson river, *Chattahoochee river, *Gas transfer, *Stream hydraulic properties

72-012

Copy available from GPO Sup Doc as EP1.23:/, $3.75; microfiche from NTIS as PB 214 649, $0.95.

17c. COWRR Field & Group 05F, 05G

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

Abstractor Richard M. Smith, Jr.

Institution Texas Univ. Austin

EPA-R3-72-012
October 1972

CHARACTERIZATION
OF
STREAM REAERATION CAPACITY

By

E. C. Tsivoglou, Principal Investigator

J. R. Wallace, Associate Investigator

Project No. 16050 EDT

Project Officer

Dr. Walter M. Sanders III
Southeast Water Laboratory
Athens, Georgia 30601

Prepared for

OFFICE OF RESEARCH AND MONITORING
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price $3.75

EPA Review Notice

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The purposes of this research have been to characterize stream reaeration capacity in terms of the stream hydraulic properties and to develop procedures for evaluating the effects of pollutants on reaeration. Field studies of the reaeration capacity and the associated hydraulic properties of five rivers have been completed, using a gaseous tracer procedure for field measurement of reaeration. These studies have incorporated a wide range of hydraulic features, such as waterfalls, rapids, shoals and pools, with stream flows ranging from 5 to 3,000 cfs. The range of BOD's and temperatures encountered was also large. Studies of the effects of both pure substances and community wastes on the reaeration capacity have been conducted in a newly designed test system.

Tests of observed vs. predicted values of K_2 have shown that none of the available models, e.g., O'Connor, Churchill, etc., is capable of providing dependable predictions of stream reaeration capacity, especially under highly turbulent flow conditions. A new energy dissipation model has been derived, by which the reaeration capacity of a stream is explained in terms of the rate of energy dissipation, measured as the loss of water surface elevation divided by the time of flow. Two distinct forms of the energy dissipation model have been tested against the observed results, and it has been shown that both forms provide dependable predictions of stream reaeration capacity.

The tests of pollutant effects have shown that LAS and community wastes decrease the reaeration rate coefficient, pure NTA has no effect, and pure mineral oil increases the reaeration rate coefficient.

This report was submitted in fulfillment of Project Number 16050 EDT, under the sponsorship of the Environmental Protection Agency.

CONTENTS

Section Page

I GENERAL SUMMARY AND CONCLUSIONS 1

II RECOMMENDATIONS 11

III INTRODUCTION 15
- Purposes of this Research 18
- Experimental Plan 19

IV RELEVANT THEORY 23
- Molecular Diffusion, Mixing and Gas Transfer 23
- Mathematical Relationships 31
- Field Tracer Application 35
- Predictive Models 38

V EXPERIMENTAL PROCEDURES 47
- Physical and Hydraulic Properties 47
- Tracer Studies 63
- DO and BOD Studies 74
- Pollutant Effects on Reaeration 74
- Settleability of Tritiated Water 78
- Sources of Error 81

VI EXPERIMENTAL RESULTS -- FIELD STUDIES 85
- Flint River 85
- South River 104
- Patuxent River 120
- Jackson River 128
- Chattahoochee River 141

VII EXPERIMENTAL RESULTS -- LABORATORY STUDIES 155
- Pollutant Effects -- Pure Substances 156
- Pollutant Effects -- River Waters 170

VIII HYDRAULIC PROPERTIES RELATED TO REAERATION 175
- Introductory Discussion 175
- Comparisons with Available Predictive Models 180
- Energy Dissipation Models -- Theory 188
- Energy Dissipation Models -- Observed Results 191
  - Flint River 192
  - South River 207
  - Patuxent River 222
  - Jackson River 229
  - Chattahoochee River 234
  - Summary Analysis -- Five Rivers 241
- Prediction of Stream Reaeration 245

Section Page

IX ACKNOWLEDGMENTS 255

X REFERENCES 257

XI PUBLICATIONS AND PATENTS 261

XII APPENDICES 263

FIGURES

		Page
1	Molecular Diffusion	25
2	Gas Transfer in Stagnant Water	27
3	Gas Transfer in Turbulent Water	29
4	Typical Cross Section Notes	49
5	Rating Curve, Flint River	50
6	Average Discharge, Flint River	51
7	Average Discharge, South River	52
8	Average Discharge, Chattahoochee River	53
9	Flow Adjustment Procedure	55
10	Measured Hydraulic Properties, Flint River	57
11	Adjusted Hydraulic Properties, Flint River	58
12	Typical Dye Curves, Flint River	59
13	Computed and Observed Velocities	60
14	Summary of Hydraulic Measurement Procedures	61
15	Tracer Release Device (Manual)	66
16	Field Sampling Arrangement	69
17	Pressure Pipette	71
18	Typical Semilog Plot of Tracer Data	73
19	Pollutant Effects Reactor	76
20	Typical Semilog Plots of LAS Data	77
21	Settleability of Tritiated Water--Experimental Arrangement	80
22	Flint River Study Locale	86
23	Channel Profile, Flint River	91

Page

24 Observed Krypton Transfer, Flint River (Upper Study Reaches) 95

25 Observed Krypton Transfer, Flint River (Middle Study Reaches) 98

26 Observed Krypton Transfer, Flint River (Lower Study Reaches) 99

27 South River Study Locale 105

28 Channel Profile, South River 112

29 Observed Krypton Transfer, South River (Upper Study Reaches) 117

30 Observed Krypton Transfer, South River (Lower Study Reaches) 118

31 Patuxent River Study Locale 122

32 Observed Krypton Transfer, Patuxent River 127

33 Jackson River Study Locale 138

34 Observed Krypton Transfer, Jackson River (Upper Study Reaches) 139

35 Observed Krypton Transfer, Jackson River (Lower Study Reaches) 140

36 Chattahoochee River Study Locale 142

37 Water Surface Profile, Chattahoochee River 148

38 Observed Krypton Transfer, Chattahoochee River 152

39 Typical Pollutant Effects Tests with LAS 157

40 Effect of LAS on K_{kr} 160

41 Effect of LAS on "ALPHA" 161

42 Typical Pollutant Effects Tests with Mineral Oil 165

43 Effect of Mineral Oil on K_{kr} 167

44 Effect of Mineral Oil on "ALPHA" 168

Page

45 Gas Loss vs. Energy Expended, Flint River (All Results) 193

46 Gas Remaining vs. Energy Expended, Flint River (All Results) 194

47 Gas Loss vs. Energy Expended, Flint River (Dump XIV) 197

48 Gas Remaining vs. Energy Expended, Flint River (Dump XIV) 198

49 Gas Loss vs. Energy Expended, Flint River (Mean Values) 201

50 Gas Remaining vs. Energy Expended, Flint River (Mean Values) 202

51 K_{ox} vs. Rate of Energy Expenditure, Flint River (All Results) 203

52 K_{ox} vs. Rate of Energy Expenditure, Flint River (Dump XIV) 205

53 K_{ox} vs. Rate of Energy Expenditure, Flint River (Mean Values) 206

54 Gas Loss vs. Energy Expended, South River (Lower Reaches) 211

55 Gas Loss vs. Energy Expended, South River (Upper Reaches) 212

56 Gas Loss vs. Energy Expended , South River (Dumps VIII and X) 213

57 Gas Remaining vs. Energy Expended, South River (Lower Reaches) 214

58 Gas Remaining vs. Energy Expended, South River (Upper Reaches) 215

59 Gas Remaining vs. Energy Expended, South River (Dumps VIII and X) 216

60 K_{ox} vs. Rate of Energy Expenditure, South River (Lower Reaches) 219

Page

61 K_{ox} vs. Rate of Energy Expenditure, South River (Upper Reaches) 220

62 K_{ox} vs. Rate of Energy Expenditure, South River (Dumps VIII and X) 221

63 Gas Loss vs. Energy Expended, Patuxent River 224

64 Gas Remaining vs. Energy Expended, Patuxent River 225

65 K_{ox} vs. Rate of Energy Expenditure, Patuxent River 227

66 Gas Loss vs. Energy Expended, Jackson River 230

67 Gas Remaining vs. Energy Expended, Jackson River 231

68 K_{ox} vs. Rate of Energy Expenditure, Jackson River 233

69 Gas Loss vs. Energy Expended, Chattahoochee River 237

70 Gas Remaining vs. Energy Expended, Chattahoochee River 238

71 K_{ox} vs. Rate of Energy Expenditure, Chattahoochee River 240

TABLES

No.		Page
1	Dosing Pattern, Flint River	87
2	Typical Hydraulic Properties, Flint River	89
3	Observed Reaeration Coefficients, Flint River	93
4	Summary of DO and BOD Results, Flint River	100
5	DO and BOD at Waterfalls, Flint River	102
6	Dosing Pattern, South River	107
7	Typical Hydraulic Properties, South River	110
8	Observed Reaeration Coefficients, South River	113
9	Summary of DO and BOD Results, South River	119
10	DO and BOD at Panola Shoals, South River	120
11	Dosing Pattern, Patuxent River	123
12	Typical Hydraulic Properties, Patuxent River	124
13	Observed Reaeration Coefficients, Patuxent River	126
14	Jackson River Station Elevations	130
15	Dosing Pattern, Jackson River	131
16	Typical Hydraulic Properties, Jackson River	132
17	Observed Reaeration Coefficients, Jackson River	136
18	Dosing Pattern, Chattahoochee River	144
19	Typical Hydraulic Properties, Chattahoochee River	146
20	Observed Reaeration Coefficients, Chattahoochee River	149
21	Reactor Tests with LAS (Constant Mixing)	158
22	Reactor Tests with LAS (Constant LAS)	162

No.		Page
23	Reactor Tests with NTA	163
24	Reactor Tests with Mineral Oil	166
25	Reaeration Effects of Pollution Loads (Weekdays)	171
26	Reaeration Effects of Pollution Loads (Sundays)	172
27	Statistical Test of Selected Predictive Models	183
28	Observed Values of the Oxygen Escape Coefficient	248

SECTION I

GENERAL SUMMARY AND CONCLUSIONS

The general purpose of the studies reported here has been to characterize the natural reaeration capacity of nontidal fresh water streams in terms of the stream hydraulic properties. The reaeration capacity controls or limits a stream's ability to receive and assimilate oxygen-depleting wastes without serious harm. This in turn dictates the necessary degree of waste treatment in any situation, and the associated costs. Hence, the reaeration capacity is a crucial and valuable natural resource. In any specific case, it is a vitally needed waste treatment design parameter, if the waste treatment facility is to be both adequate and economical. Hence, the ability to predict stream reaeration capacity with accuracy and within acceptable limits of error has long been an urgent need.

In any stream, the ability to absorb oxygen from the atmosphere, or the reaeration capacity, is a direct function of the degree of turbulent mixing. Atmospheric oxygen can be obtained only at the water surface, and the rate at which reaeration can take place is therefore directly limited by the rate of surface water replacement in a flowing stream. Thus, in a relatively still pool reaeration is a very slow process, whereas the reaeration capacity of a rapids section is very great. In turn, in any stream the rate of water surface replacement is controlled by the stream's physical characteristics, and is related to the associated hydraulic properties.

Attempts to predict stream reaeration capacity from the hydraulic properties date back to 1911, to the work of Black and Phelps, who proposed a predictive model based upon stream depth and a "mixing period." In 1925, Streeter and Phelps proposed a new model relating the reaeration capacity to the velocity and depth of flow. The predictive models proposed by others since that time have largely followed the same empirical form. Until 1966 it was not possible to test any of the available predictive models against independent field observations of stream reaeration capacity, as there was no method of measuring reaeration capacity directly and independently. As a result, it was not possible to evaluate the accuracy or dependability of any of the available predictive models, or to select the best among them, before that time.

In 1966 the first direct and independent field measurements of stream reaeration capacity were made in the Jackson

River, below Covington, West Virginia. Those measurements were made by means of a new field tracer procedure developed by the Federal Water Pollution Control Administration, in which a radioactive form of the noble gas krypton serves as a tracer for oxygen. LImited hydraulic studies were conducted at the same time, and the Jackson River studies thus also provided the first test of the more commonly used predictive models. That test, limited to one stream section having a very narrow range of reaeration capacities, was not conclusive, but did indicate that the two most commonly used predictive models provided estimates in the general range of observed results.

The field tracer procedure for measuring stream reaeration capacity has since been applied in detailed studies of four additional streams. These studies provide the information presented in subsequent sections of this report. During the period 1969-1971 studies were conducted in sections of the Flint, South, and Chattahoochee Rivers, in Georgia, and the Patuxent River in Maryland. In all, including the earlier Jackson River studies, a total of 323 measurements of the reaeration rate coefficient, K_2, have been made and are reported here. They refer to a total of about 70 miles of stream including rapids, waterfalls, shoals, pools and relatively uniform stream reaches. In the various field studies the stream flow has ranged from as little as 5 cfs to as much as 3,300 cfs, and the river temperature from 10°C to 35°C; the 5-day BOD of the streams has ranged from about 3 to 30 mg/l, and the observed values of K_2 from zero to 15.0/hr. Thus, the available observed results are regarded as representative of a great many, probably most, nontidal fresh water streams. They have provided the basis for a new energy dissipation theory of reaeration, as well as the necessary field data for adequate testing of currently available predictive models.

It has been known for some time that pollutants such as detergents may affect stream reaeration capacity, and an additional purpose of this research has been to develop a procedure for accurate evaluation of such effects. A laboratory procedure capable of measuring the effect of wastes on reaeration capacity has been developed, and has been applied in studies of the effect of pure substances (LAS, NTA, mineral oil) and of the pollution present in river waters. These studies have proved also to be of considerable assistance in characterizing stream reaeration capacity.

A more detailed, referenced, review of the historical development of predictive models for stream reaeration capacity is provided in Section IV of this report, together with a detailed discussion of the relationships between turbulence, mixing and gas transfer. All of the experimental procedures are described in Section V, including the gaseous tracer field method for reaeration measurement, physical (hydraulic) field measurement procedures, and the laboratory system for testing the effects of pollutants. All of the observed field results are presented and discussed in Section VI, and the pollutant effects results are provided in Section VII. Section VIII of the report includes the theoretical development of the energy dissipation models for predicting reaeration capacity, as well as the detailed results of statistical testing of these and other available predictive models. Finally, Section VIII includes recommended models and procedures for the prediction of stream reaeration capacity.

One additional purpose of this research was to make available a complete set of data, both reaeration and hydraulic, for the use of others in conducting further tests of available models, or refining them, and in developing new predictive models. Accordingly, all of the detailed tracer study and hydraulic study data have been summarized and are provided in Appendices to this report.

CONCLUSIONS

The following conclusions have been derived from and are supported by the research studies reported here.

(1) The reaeration capacity of nontidal fresh water streams is directly related to the energy expended by the flowing water. Reference to the energy equation for flow in open channels indicates that the reaeration capacity is directly related to the change of water surface elevation. The change of water surface elevation between two stream locations is just the amount of energy expended in that reach, in ft-lbs per pound of water; the change in water surface elevation divided by the time of flow is the average rate of energy expenditure.

(2) The reaeration rate coefficient is directly proportional to the rate of energy expenditure in nontidal fresh water streams. This basic relationship may be expressed by the model

$$K_2 = c(\frac{\Delta h}{t_f}) \qquad (48)$$

where K_2 is the reaeration rate coefficient (base e) per hour, t_f is the time of flow in hours, Δh is the water surface elevation change in feet, and c is the constant of proportionality with units per foot. Other compatible sets of units may be substituted as desired.

(3) From equation (48) and the basic reaeration equation, the amount or extent of reaeration that takes place in streams such as those included in these investigations can be related to the amount of energy expended by the following model:

$$\frac{D_2}{D_1} = e^{-c\Delta h} \qquad (61)$$

where D_1 is the DO saturation deficit at the upstream end of a stream section, in mg/l, D_2 is the DO saturation deficit, in mg/l, that would occur at the downstream end if there were no concurrent sources of oxygen consumption in the stream section, Δh is the water surface elevation change in the section, in feet, and c is the same constant of proportionality that occurs in equation (48).

(4) The constant of proportionality, c, that occurs in equations (48) and (61) is designated the "escape coefficient." It is the product of two other constants

$$c = (a) \times (b) \qquad (57)$$

one of which, a, refers solely to the physical molecular properties of the diffusing gas and the quality of the water, and the other, b, refers exclusively to the mixing characteristics and hydraulic properties of the stream. From equation (61) above

$$c = \frac{0.693}{(\Delta h)_{1/2}} \qquad (52)$$

and the escape coefficient may thus be regarded as a "half-height", in feet; the half-height is that amount of water surface elevation change required for D_2 to take the value 0.50 D_1. If the half-height for a particular stream were 10 feet, and there were no sources of concurrent oxygen consumption, then 50 percent of an initial DO deficit would be satisfied in 10 feet of fall, 75 percent in 20 feet, etc.

For any stream section, the escape coefficient is a basic constant that will remain unchanged unless the degree or kind of pollution is changed or the hydraulic mixing regime is altered significantly.

(5) The escape coefficient, c, is related to the water temperature in the same way as K_2, namely

$$\frac{c(T_2)}{c(T_1)} = \frac{K_2(T_2)}{K_2(T_1)} \approx \frac{C_s(T_1)}{C_s(T_2)} = 1.022^{(T_2-T_1)} \tag{62}$$

within the range 0°C to 30°C, where T_1 and T_2 are the water temperatures in °C, $C_s(T_1)$ and $C_s(T_2)$ are the respective DO saturation limits in mg/l, and the constant $\theta = 1.022/°C$ has been derived and demonstrated elsewhere (see Section IV).

(6) The foregoing energy dissipation models for stream reaeration capacity, equations (48) and (61), have been tested by standard statistical procedures for each of the five streams studied, with very satisfactory results. In all cases equation (61) produced high correlation ($r_{xy} = 0.90$ or better); equation (48) produced comparable results except in streams where the observed range of K_2 was very small. The numerical values of the escape coefficient, c, derived from separate statistical tests of equations (48) and (61) were in excellent agreement in every case.

(7) The range of numerical values taken by the escape coefficient, c, is quite small. For the five rivers studied, which incorporate a very wide range of stream flow, BOD, temperature and K_2, the range of individual values of c was from 0.0317/ft to 0.0804/ft at 25°C. It appears unlikely that for any stream that is reasonably well mixed the escape coefficient will be much less than 0.030/ft or much greater than 0.085/ft at 25°C.

(8) From summary analyses of the observed results for all five rivers taken together, the single value c = 0.054/ft at 25°C was obtained. All of the observed values of c from the individual river studies fall within ± 50 percent of that result. From those analyses the models

$$K_2 = 0.054 \left(\frac{\Delta h}{t_f}\right) \tag{59}$$

and

$$\frac{D_2}{D_1} = e^{-0.054\Delta h} \tag{58}$$

may be used to estimate the reaeration capacity of an "average" or "typical" stream that is moderately polluted (5-day

BOD in the neighborhood of 15 mg/l) and reasonably well mixed, at a temperature of 25°C.

(9) The observed range of numerical values taken by the escape coefficient, c, appears to be related primarily to the degree of pollution of the stream. Thus, the highest observed values of c were associated with the least pollution, measured roughly as 5-day BOD, and vice versa. However, the available results do not indicate an exact or exclusive relationship between c and the 5-day BOD, and this matter requires more extensive investigation. For the present, the predictive equations (58) and (59) may be modified with caution by substituting a lower value of c (down to 0.030/ft) for streams that are relatively heavily polluted (up to about 30 mg/l of 5-day BOD), or a higher value (up to c = 0.085/ft) for streams that are relatively lightly polluted (down to 2 mg/l or so of 5-day BOD).

(10) In sections of stream where the entering flow clearly does not mix fully with the whole stream volume, as may occur in stratified pools, reservoirs and estuaries, great care is necessary in predicting reaeration capacity at any time. Under such hydraulic circumstances, the entering stream flow may gain substantially more oxygen than expected if it tends to remain at the water surface, or it may gain essentially no oxygen by direct reaeration if it flows along the stream bottom. Such a situation can be unusually sensitive to transient meteorological and hydrologic conditions in terms of their effect on the mixing regime at any time.

(11) These studies have indicated that the mixing pools that occur underneath waterfalls may add significantly to the reaeration that would otherwise take place. Observed results are for only one such pool, and the available data are not sufficient to develop an accurate relationship, but indicate that the degree to which such pools enhance reaeration may well be directly related to the ratio of stream flow (and energy input) to pool volume, as well as the specific geometry involved.

(12) The available results suggest strongly that stream flow changes by a factor of two or three do not usually significantly modify the stream reaeration capacity. Flow changes of that order had no significant effect upon the magnitude of K_2 in the Flint, South, Patuxent or Chattahoochee Rivers. A flow increase reduces the time of flow, but not usually in the same proportion; this flow increase also therefore reduces the period in which gas transfer may take place. Other changes in hydraulic properties, such as the slope of the water surface, velocity, depth, etc., also

occur with changes in discharge. In essence, changes of flow by a factor of two or three appear to have little effect on K_2, and, by inference, on the mixing regime. The available data are not sufficient to further clarify this matter. For the present, however, they indicate clearly that K_2 is not usually significantly affected by flow changes of the order mentioned above.

(13) Laboratory tests with the detergent LAS have demonstrated that LAS reduces the reaeration capacity of water. In a series of tests at a constant mixing rate, the gas transfer capacity of distilled water decreased to about 60 percent of the unpolluted magnitude as the LAS concentration was increased to 12 mg/l. Additional tests at a constant LAS concentration showed that the gas transfer capacity also decreased as the rate of mixing was increased. Thus, LAS and similar pollutants appear to bring about the greatest reduction of reaeration capacity at features such as rapids and shoals in streams, where reaeration would otherwise be expected to be at a most beneficial maximum.

(14) Laboratory tests with mineral oil have demonstrated that mineral oil enhances the gas transfer capacity of water. A series of laboratory reactor tests at a constant mixing rate showed that the gas transfer capacity of distilled water more than doubled as mineral oil concentration was increased to 400 mg/l. A small number of tests at a constant concentration of mineral oil showed that as the mixing rate was increased the effect on gas transfer capacity diminished. Concentrations of oil in river waters should be much lower than these laboratory test concentrations except for major accidental spills, and these results are therefore not regarded as applicable to practical stream reaeration problems at this time.

(15) A small number of laboratory tests with pure NTA indicated that NTA itself has little or no effect upon the gas transfer capacity of water. In tests with NTA concentrations up to 16 mg/l no significant change in the gas transfer capacity of distilled water was observed.

(16) Tests with natural river waters have demonstrated that the pollution added to streams causes reduction of the stream reaeration capacity. For these tests, the gas transfer capacity of "clean" Chattahoochee River water (taken at the Atlanta Water Works) was compared to that of polluted river water (taken below the Clayton STP). The gas transfer capacity of South River water samples had to be compared to that of distilled water, as no relatively "clean" South River location was available. The South River water samples

had about 80 percent of the gas transfer capability of distilled water. On weekdays, the gas transfer capability of the polluted Chattahoochee water was considerably less than that of the "clean" Chattahoochee water. On Sundays, when pollution of the Chattahoochee is considerably reduced, there was no significant difference between the gas transfer capabilities of Chattahoochee River water from the "clean" and polluted locations.

(17) Earlier models for predicting stream reaeration capacity from the hydraulic properties have been tested by standard statistical procedures against the results observed in this research and reported here. None of those models proved capable of predicting stream reaeration capacity within acceptable limits of error over the range of observed results. The differences between predicted and observed values of K_2 were consistently large for highly turbulent stream reaches and reaches where flow was not uniform.

(18) The stream hydraulic properties that are related to reaeration in a primary way are the change in water surface elevation and the time of flow. The slope of the water surface, or the change in elevation per unit length, is thus a primary or causative hydraulic property. The change in water surface elevation per unit time, or the rate of energy dissipation, is a basic dynamic hydraulic property. It has been shown by these studies that the range of observation of the rate of energy dissipation is quite comparable to the range of associated values of K_2, and that the rate of energy dissipation is a sensitive indicator of stream reaeration over a very wide range of observation.

(19) Neither the mean forward velocity nor the mean depth of flow appear to be related to stream reaeration in a primary way. The mean velocity results from the slope of the water surface and the energy gradient, and is a secondary property in that sense; it has been shown that the range of observable mean velocities is very much smaller than the range of associated values of K_2, and thus the former cannot be a highly useful indicator of the latter. Stream depth appears also to be a secondary property. In a turbulent stream there is no apparent reason why depth, per se, should control or limit reaeration. As in the case of mean velocity, the observed range of stream depths has been shown to be much smaller than the observed range of values of K_2, and depth therefore cannot be a sensitive indicator of reaeration.

It has been clearly shown in the studies reported here that most of the real work of gas transfer takes place at abrupt changes of elevation such as rapids, shoals and falls in reaches that contain such features. In such reaches, neither the mean velocity nor the mean depth of flow can be regarded as a meaningful or adequate indicator of turbulence or gas transfer.

(20) Stream bottom roughness is a calculated rather than an observable or measurable property, and may be calculated only for quite restrictive conditions of uniform flow. Many if not most of the stream sections studied failed to meet the criteria for uniform flow. Hence, the bottom roughness is not regarded as a useful indicator of stream reaeration capacity.

(21) It became evident early in the studies reported here that longitudinal dispersion could not serve as a useful general indicator of natural stream reaeration capacity. At hydraulic features such as waterfalls, rapids and shoals, a great deal of reaeration occurred even though there was virtually no longitudinal dispersion across those features. Accordingly, no further analysis seeking a relationship between reaeration and longitudinal dispersion was conducted.

(22) The gaseous tracer procedure for direct field measurement of stream reaeration capacity is suitable and effective for stream flows at least as large as 3,300 cfs, without significant radiation exposure of field personnel or any member of the public, and without unduly cumbersome or impractical field procedures or equipment. For the larger doses required for large stream flows, the field dosing procedure should be designed to minimize handling the dose and to minimize the duration of any exposure of the dosing party. The use of blasting caps for dose release and of downstream hand sampling procedures for dose assay have proved to be effective methods for minimizing personnel exposure and obtaining the necessary information. These procedures are described in more detail in Section V of this report.

(23) The reproducibility of results obtained by use of the gaseous tracer method for stream reaeration capacity has proved to be generally excellent throughout these studies, with few exceptions. In stream reaches where mixing is very poor and even erratic, the actual reaeration that takes place at any time will depend upon the momentary mixing situation, and an individual field measurement of reaeration therefore may not always reflect "average" conditions. Such situations include, for example, pooled reaches that are subject to thermal stratification wherein the entering stream flow may either stay at the surface or flow along the bottom of the pool, depending upon momentary conditions. Where the magnitude of the reaeration coefficient, K_2, is small and approaches the magnitude of the error associated

with any individual measurement of K_2, the accuracy of any individual measurement may be improved by counting larger numbers of samples and by extending the counting period; if necessary, several such measurements of K_2 can also be made to arrive at a satisfactory mean value.

(24) The basic energy dissipation models, equations (48) and (61), describe the transfer of many gases, not just oxygen, with appropriate modification of the magnitude of the escape coefficient. It has been demonstrated elsewhere both theoretically and experimentally that for any pair of different gases

$$\left(\frac{K_A}{K_B}\right) = \left(\frac{D_{mA}}{D_{mB}}\right) = \left(\frac{d_B}{d_A}\right) \tag{6}$$

where A and B denote the two different gases, K is the gas transfer coefficient (K_2) for the specific gas, D_m is the molecular diffusivity, and d is the molucular diameter (see Section IV and related references). The escape coefficient is also specific for any gas, and is proportional to the K_2 for that gas. Hence, equation (6) may be rewritten

$$\left(\frac{c_A}{c_B}\right) = \left(\frac{K_A}{K_B}\right) = \left(\frac{D_{mA}}{D_{mB}}\right) = \left(\frac{d_B}{d_A}\right) \tag{63}$$

where c_A and c_B are the escape coefficients for the two gases.

As an example of the usefulness of equation (63), the predictive model for oxygen transfer in a "typical" stream, equation (59), may be readily converted to a predictive model for the transfer of carbon dioxide, or nitrogen. Using either the ratio of known diffusivities for oxygen and CO_2, or the ratio of known molecular diameters

$$(K_2)_{CO_2} = 0.047 \left(\frac{\Delta h}{t_f}\right) \tag{64}$$

Similarly, for nitrogen

$$(K_2)_{N_2} = 0.049 \left(\frac{\Delta h}{t_f}\right) \tag{65}$$

These models refer only to the physical transfer of the dissolved gases into or out of the water. They do not include the additional chemical reactions that may also take place, such as the pH-dependent behavior of CO_2 in water.

SECTION II

RECOMMENDATIONS

The studies reported here and the conclusions derived from them are subject to certain limitations, as outlined in the text of this report and in Section I. The following recommendations, if carried out, should be of considerable assistance in refining and expanding the ability to predict stream reaeration capacity.

(1) It is recommended that studies designed to firmly establish the range of the escape coefficient, c, be undertaken. At the one extreme, this will require evaluation of c for clean natural streams and reaches that receive only highly treated secondary or tertiary effluents. At the other extreme, it will require similar studies in stream reaches that are heavily polluted by representative community and industrial wastes.

(2) As shown in equation (57), the escape coefficient, c, is the product of two other constants, a and b, for any stream. The latter is a mixing coefficient, dependent upon the specific hydraulic properties and mixing characteristics of the stream. The former, a, is a molecular coefficient, related only to the physical molecular properties of oxygen and the quality of the water. The coefficient, a, is thus related to the diffusivity, but is affected by pollutants. It is recommended that studies be undertaken to establish the magnitude of the coefficient, a, for clean water. This will facilitate evaluation of the effects of pollutants on a, and will allow separate evaluation of the specific mixing characteristics of a stream.

(3) Research studies designed to clarify the basic mechanisms by which pollutants modify the gas transfer capacity of water are strongly recommended. The observation reported here that LAS and mineral oil have opposite effects on K_2 demonstrates the importance of such research. It appears from these limited studies that entire classes of pollutants may enhance reaeration capacity, whereas others may reduce it. As indicated in Section VII, presently one can only speculate on the mechanisms involved: they may include alteration of the water surface on a molecular scale, changes in surface tension, modification of the hydraulic characteristics of the whole body of fluid, or other factors not presently envisioned. Clarification of these mechanisms, and of the characteristics of pollutants that bring them into play, should be of particular assistance in refining the ability to predict stream reaeration capacity.

(4) A suitable and accurate test system for measuring the effect of pollutants on the DO saturation concentration should be developed. The reactor test system used here (see Section VII) provides for tests of pollutant effect on K_2, but no studies of the effect on DO saturation have been performed, nor any tests devised for that purpose. It appears likely that some pollutants may modify the DO saturation limit as well as the reaeration rate coefficient, and such an effect would be of considerable importance in planning for waste control.

(5) Detailed investigations of the effects of typical wastes on stream reaeration capacity are recommended. Such information should be of great assistance in planning for the location and eventual growth of industry, as well as for assigning economic damages to waste sources and allocating stream self-purification capacity. The required studies can be performed in reactor experiments of the type reported here (see Section VII), on a somewhat larger scale. Typical process wastes from paper and textile mills, food processing plants, chemical production facilities, refineries, etc., should be studied for their effect on K_2, with reference to both waste concentration and degree of turbulent mixing. Concurrent studies of any effect on the DO saturation concentration should also be performed.

(6) Further studies of the specific relationships between stream flow and reaeration capacity are recommended. Changes in stream flow modify a number of hydraulic properties, and in varying degree. It has been found in the studies reported here that changes in stream flow by a factor of two or three had no significant effect on the reaeration rate coefficient, and that implies that flow changes of that magnitude did not significantly modify the mixing regime. It is recommended that studies of the relationship between flow and K_2 be undertaken to clarify this matter. Such investigations should be performed in selected natural stream channels, and in each case should involve a sufficiently wide range of flow to provide positive results.

(7) Thorough studies of the relationships between energy dissipation and reaeration should be conducted for specific hydraulic features such as waterfalls, mixing pools, hydraulic jumps, spillways, etc. Such investigations may be carried out principally and most readily in hydraulic laboratory models, using the tracer method for reaeration capacity, but should also include prototype studies to the extent necessary to verify scaling factors. For each specific feature, energy expenditure and gas transfer capacity should be interpreted in terms of prominent hydraulic characteristics such as height of free fall, height of hydraulic jump,

mixing pool retention period, flow (and energy) to channel volume ratio, etc. Such research studies should be of particular aid in the design of stream hydraulic structures for maximum reaeration effect, as well as in refining the ability to predict the reaeration capacity of natural streams.

(8) It is recommended that research on the reaeration capacity of tidal waters and estuaries be performed. The studies reported here have been restricted to nontidal fresh water streams, but do provide some insight regarding tidal waters. Tides represent an additional or superimposed energy input that should, by itself, usually cause additional mixing, surface water replacement and reaeration. For example, it appears that at any location the reaeration capacity may prove to be a direct function of the water surface elevation change associated with high and low tides, as well as the ratio of fresh water inflow to occupied channel volume. The necessary studies may well be carried out largely in the hydraulics laboratory and in river basin models such as those located at the Waterways Experiment Station of the US Army Corps of Engineers, at Vicksburg, Mississippi, but scaling factors will have to be verified in the prototypes. The reaeration capacity of tidal waters and estuaries is a matter of great economic importance in coastal regions of the United States, and the proposed research studies should therefore be of considerable practical value.

(9) It is recommended that responsible state and federal agencies develop and undertake long-term programs designed to obtain and accumulate accurate information regarding water surface elevation change and time of flow for important sections of streams of the United States. It has been shown by these studies that water surface elevation change and time of flow are the basic hydraulic data required for prediction of natural stream reaeration capacity, and the recommended program should be of great value for planning purposes, as well as for solution of immediate waste control problems. In the interests of efficiency and economy, the more critical stream reaches below communities and industries should be studied early in the program, and the stream sections studied should be of sufficient length to include both the critical and recovery zones. In situations where secondary waste treatment may not provide adequate protection of stream oxygen resources, as indicated by the predicted reaeration capacity, tracer measurement of the reaeration capacity at appropriate low stream flows is recommended.

(10) It is recommended that the field data obtained by Churchill et al[5] for TVA streams be restudied in terms of the energy dissipation models for reaeration capacity, equations (48) and (61). Those data represent the only other available set of real field observations of recent times. Even though they were derived by the indirect oxygen balance method, it appears that the reported values of K_2 should not contain large error for the most part, as great care was exersized to prevent error due to photosynthesis, BOD, sludge demands, etc. Hence, the observed results may well provide an independent means of studying the energy dissipation models and of deriving valid estimates of the escape coefficient for relatively clean natural stream sections.

SECTION III

INTRODUCTION

The ability of a flowing stream to obtain oxygen from the limitless resources of the atmosphere is the fundamental process by which the stream is able to "purify itself" once its dissolved oxygen resources have been depleted. Without this "reaeration capacity", a stream degraded by oxygen-depleting wastes could never recover its dissolved oxygen resources, and the great variety of natural aquatic life that is taken for granted could not exist. Thus, accurate knowledge of the reaeration capacity of a polluted stream is the necessary basis for determination of waste treatment requirements, if oxygen resources are to be adequately protected, and is thereby also the principal requirement for accurate evaluation of the costs of pollution control. For these reasons, attempts to evaluate stream reaeration capacity date back at least to 1911[1], and research on this subject has intensified in recent years as population has expanded and stream pollution has become a more widespread and more serious national problem.

The reaeration capacity of a flowing stream depends primarily upon the prevailing degree of turbulence of the stream. Oxygen transfer from the atmosphere into the water can take place only at the air-water interface that exists at the stream surface, and this interface is constantly and randomly changing (being replaced or renewed) due to turbulent mixing of the flowing water. Hence, for any specific degree of oxygen depletion, the rate at which oxygen can be gained by the flowing water is directly proportional to the rate at which the water surface is being replaced from below by turbulent mixing.

Turbulence is a very complex process, and is not as yet susceptible to independent measurement or evaluation. As a result, we have had no independent means of knowing the rate of water surface renewal in a natural stream, and it has therefore not been possible to evaluate reaeration capacity in terms of stream turbulence. It has thus been necessary over the years to attempt to evaluate stream reaeration capacity by the indirect oxygen balance method of Streeter and Phelps[2].

Stream self-purification involves two principal processes, namely: (a) the depletion of DO resources by bacterial degradation of domestic and industrial organic wastes, and

(b) the replenishment of the DO resource by absorption of oxygen from the atmosphere. Other natural processes modify the oxygen balance in a polluted stream or reservoir: the anaerobic decomposition of benthal deposits of settleable organic matter results in a local demand on the DO resources of the stream; if algae are present in large numbers, they will add oxygen to the stream by photosynthesis during daylight hours and will consume DO by respiration during the dark hours; in some streams, prolific growths of attached bacterial slimes have a great influence on the oxygen content of the flowing water; the situation is often further complicated by the presence of multiple sources of pollution and tributary flows. All of these oxygen-influencing processes occur simultaneously in a polluted stream, to lesser or greater degree, and in a specific case any one of them may dominate the total self-purification process. Stream self-purification is thus a very complex process in any real situation.

In applying the Streeter-Phelps indirect oxygen balance procedure, an attempt is made to evaluate all of the other processes that have influenced an observed stream DO profile, and then a calculation is made of what the reaeration oxygen income must have been in order to produce the observed DO profile. The approach is much the same as that used in estimating the bottom "roughness" of a stream in calculations related to open channel flow - one cannot obtain a system-independent direct measure of roughness.

The several oxygen-influencing processes that occur in a natural stream are not all susceptible to accurate independent evaluation, either. Thus, although the indirect oxygen balance procedure is entirely logical and valid in concept, its application incorporates unavoidable errors of assumption, omission and field measurement. The net result is that indirectly calculated estimates of reaeration capacity contain an unknown degree of error, small in some cases and undoubtedly large in others. In point of fact, the reaeration rates calculated by the indirect method contain an error that simply compensates for all of the other errors of assumption, omission and measurement that have been made. As a result, it has not been possible to accept such indirect estimates of reaeration as firm or accurate.

Until quite recently, then, it has not been possible to obtain firm and accurate evaluations of the reaeration capacity of a polluted stream - we have not known how to evaluate turbulent mixing, which controls reaeration, and we have not known how to obtain accurate independent evaluations of some of the other oxygen-influencing processes such as photosynthesis and bioextraction.

Faced with the above dilemma, various investigators have attempted over the past 60 years to develop rational mathematical models for the reaeration process itself. Such models generally attempt to explain reaeration in terms of turbulence theory and stream hydraulic properties such as velocity and depth of flow. The first such model was provided in 1911 by Black and Phelps, in a report on the pollution of New York Harbor[1]. That model, which attempted to explain reaeration in terms of molecular diffusion, stream depth and a "mixing period", is still in use today[3].

Since 1911, other attempts have been made to explain reaeration in terms of the hydraulic properties that are associated with turbulent mixing. Some of the better known models include those of Streeter and Phelps (1952)[2], O'Connor and Dobbins (1956)[4], and Churchill et al (1962)[5], all of which consider reaeration (and turbulence) to be directly related to stream velocity and inversely related to stream depth. Other models include that of Krenkel and Orlob[6] who attempted to explain reaeration in terms of longitudinal dispersion, and the Thackston model[7] which incorporates hydraulic slope as an additional influencing factor.

All such mathematical models for stream reaeration are referred to here as predictive models, rather than indirect, as their purpose is to predict reaeration independently in terms of stream hydraulic properties. In all cases, their development has been hampered and limited because the only means of testing the model has been indirect calculation of the real reaeration income by the questionnable oxygen balance procedure. Hence, all of the predictive models must still be regarded as possible but not proved.

The predictive models for reaeration will be discussed in greater detail at a later point. They are regarded as most important, as they represent the necessary direction of development, that is, the explanation of stream reaeration, and the ability to predict it, in terms of hydraulic properties. Thus, although any or all of the predictive models may prove eventually to be not quite adequate or correct, all of them provide necessary emphasis and insight into the important relationships between reaeration, gas transfer and turbulent mixing in natural streams.

Recognizing the real need for an independent means of evaluating stream reaeration capacity with accuracy and dependability, in 1964 The Federal Water Pollution Control Administration began studies to develop such a procedure. The result of those studies has been the gaseous tracer procedure that forms the basis of these research studies[8].

The tracer method for reaeration was first demonstrated in the field in 1966, in studies of self-purification of the Jackson River below Covington, West Virginia[9]. Those field studies fully demonstrated the techniques and the effectiveness of the reaeration tracer procedure, and produced the first independent observations of stream reaeration capacity. The gaseous tracer procedure is described in full detail in a 1967 FWPCA report[10], which also contains a detailed theoretical discussion of the mechanisms of gas transfer in turbulent water systems. Counting the studies reported here measurements of reaeration capacity have now been conducted in six or more inland streams, in a small tidal estuary, and in a physical model of a tidal stream.

PURPOSES OF THIS RESEARCH

The gaseous tracer procedure for field observation of stream reaeration capacity now provides the necessary tool for characterizing stream reaeration capacity in terms of the hydraulic properties associated with turbulence, and, hence, for solving the practical problem of predicting reaeration from field measurements of the relevant stream hydraulic properties.

Although the tracer method permits highly accurate field evaluation of reaeration capacity in specific stream sections, such observations are not directly extendable to other streams. The field method itself is not without certain limitations and disadvantages related to cost, availability of special equipment and specially trained personnel, and radiological safety, and widespread application of the field tracer procedure by practicing sanitary engineers is regarded as both unlikely and unnecessary. In many practical situations all that is needed is a proved hydraulic model for reaeration that provides predictions within acceptable limits of error. The general purpose of this research has therefore been to provide such a predictive model for general use, and to investigate its limitations and range of error, so that the field tracer procedure may be reserved for application in situations where the highest degree of accuracy and dependability is a necessity.

The specific purposes of this research have been as follows:

(1) on the basis of direct field measurements of reaeration capacity and hydraulic properties, to evaluate the degree of accuracy and the range of error normally associated with the various available predictive models for reaeration capacity;

(2) by means of direct field tracer and physical studies in local streams, to define and evaluate the basic relationships between stream reaeration capacity and measurable stream hydraulic properties such as depth and velocity of flow, slope, dispersion, etc.;

(3) as necessary, to develop modified predictive models, or additional models, for predicting stream reaeration capacity on the basis of measurable hydraulic properties;

(4) to refine and perfect the field methodology for the use of the gaseous tracer procedure in large river flows;

(5) to develop and demonstrate a standard laboratory test procedure for evaluating the actual effects of pollutants on stream reaeration capacity, and to apply this technique to evaluate the effects of various pollutants such as detergents, oils, municipal wastes, etc.

As incidental but not negligible purposes, it was planned that the research program would provide useful and necessary reaeration data to be of assistance in solving real pollution problems in the local vicinity, and that it would also provide a complete set of basic field data on reaeration and hydraulic properties to be available to other investigators who might wish to perform independent analysis of the basic relationships involved.

EXPERIMENTAL PLAN

The general plan of research included concurrent field and laboratory investigations designed to satisfy the foregoing purposes to the full extent possible, the field and laboratory studies being mutually complementary rather than separate project areas. Field studies in at least two small (less than 250 cfs) local streams were planned as the initial project phase, to be followed by similar studies in a larger stream (1,000 cfs, or greater) as the second project phase. It was planned that each field study would include gaseous tracer evaluation of the reaeration capacity through the critical pollution zone and into the recovery zone, together with supporting stream physical and limited oxygen balance studies. The streams finally selected for study were the Flint River below the Atlanta airport, the South River below the South River Sewage Treatment Plant, and the Chattahoochee River below the Clayton Sewage Treatment Plant in Atlanta.

As planned, the gaseous tracer studies employed essentially the same field procedures as described in earlier reports[8, 9,10], with krypton-85 used as the tracer for dissolved oxygen, tritiated water as the dispersion indicator and a fluorescent dye (rhodamine-WT) for evaluation of time of flow and longitudinal dispersion. It was planned that the field physical studies would be conducted prior to or concurrently with the tracer studies, and would include flow gaging according to accepted USGS procedures, stream cross-sectioning (usually at 500-foot intervals) and determination of stream slope. The resulting data should provide adequate information regarding stream flow, hydraulic slope, cross-sectional area, mean velocity and depth, etc. Concurrently with the tracer studies, it was also planned to conduct limited oxygen balance studies for purposes especially of observing any unusual effects such as might result from the occurrence of prolific growths of algae or attached bacterial slimes. It was planned to conduct all of the field studies during periods of extended low flow and relatively high stream temperature, to the extent possible, in order to obtain maximum relevant information.

The planned laboratory research included studies as necessary to develop the tracer method further for application to larger stream flows, and studies to measure the effects of various pollutants of interest on the reaeration capacity. The investigations envisioned for extension of the tracer method to larger flows involved both the possibility of shielding the necessary tracer doses in lead pigs (and remote dosing, if necessary for personnel protection), and substitution of a less hazardous radiotracer gas (xenon-133) for krypton-85 as the tracer for dissolved oxygen. As the research developed, it became evident that krypton-85 doses as large as 5.0 or more curies could be used safely without lead pigs or other such special protection, and that doses of that magnitude were adequate for measuring gas transfer in flows up to 3,000 cfs. Hence, it proved unnecessary to investigate the possible substitution of xenon-133 for krypton-85.

The experimental plans also called for the development of a standard laboratory reactor test for pollutant effects on reaeration, envisioning a series of reactor tests using stream receiving water from above the pollution source and, subsequently, water taken from below the source of pollution. As the research developed, these plans were modified to include investigation of the effects of pollutants such as LAS, NTA and oil, in order to develop basic information regarding the effects of such surface active agents and surface contamination on the gas transfer capacity of water. Although not originally planned, other laboratory investigations were also conducted, including, for example, limited investigations of the possibility (suggested by others) that tritiated water might physically separate from ordinary water because of settling of the heavier tritiated water molecules.

As is the case with any research project, the initial research plans were modified as research information became available during the course of the project to the extent deemed necessary to best satisfy major project purposes.

SECTION IV

RELEVANT THEORY

The following summary of theoretical considerations that are relevant to this research represents the available necessary theory as of the time when this research was begun. This summary has been taken largely from the 1967 FWPCA report on this subject[10], and the reader is referred to that report for specific mathematical derivations and proofs of interest. No attempt has been made here to include all of the various theories regarding reaeration that are available in the extensive earlier literature on this subject. Rather, only directly relevant and necessary theory is included here. An excellent comprehensive 'state-of-the-art' review of all of the available literature on oxygen transfer in water has been completed recently by King[11], and the reader is referred to that report for additional information and references.

MOLECULAR DIFFUSION, MIXING, AND GAS TRANSFER

Reaeration of turbulent water is a purely physical process that involves entry of the oxygen molecules from the atmosphere into the water at the air-water interface and subsequent distribution of this dissolved oxygen throughout the volume and depth of water. Reaeration takes place as the result of the combined effects of molecular diffusion of the oxygen and physical mixing of the water. The driving force for reaeration is the difference between the active partial pressures of oxygen in the air and in the water. In a polluted stream, the water is oxygen-deficient, the driving force is in the air-to-water direction, and this brings about a net transfer of oxygen from the air to the water. So long as such a driving force exists, oxygen transfer will take place. When the driving force has disappeared, and there is no longer any partial pressure difference, the water is said to be "saturated" with dissolved oxygen. For example, at 20°C and one atmosphere of air pressure the "saturation limit" for dissolved oxygen in water is 9.17 mg/l, and this is the maximum attainable DO concentration. The "saturation deficit" is the difference between the actual concentration of the DO in the water and the saturation limit for the existing temperature and pressure, and is a measure of the strength of the driving force for reaeration.

Molecular diffusion and physical mixing, or dispersion, are two quite different processes that complement each other during reaeration of turbulent water. As outlined below, diffusion takes place because of the inherent kinetic energy

Preceding page blank

possessed by the oxygen molecules, whereas the dissolved gas molecules are dispersed by turbulent mixing, which results from the application of external forces of one kind or another on the volume elements of water. The technical literature is somewhat confusing on this point - for instance, the commonly-used terms 'eddy diffusion' and 'hydrodiffusion' really refer to mixing or dispersion of the volume elements of water, rather than to the molecular diffusion process so well known in science.

It is also important to bear in mind throughout the following discussion that the water can obtain additional oxygen only at the air-water interface, or the water surface.

MOLECULAR DIFFUSION

If a group of dissolved molecules (such as a salt or a gas) could be placed at some point in a beaker of water, and if this could be accomplished without disturbing the water, the dissolved molecules would: (a) gradually spread out through the water volume, and (b) eventually achieve a uniform concentration throughout the volume of water in the beaker. They would do this without any movement at all of the water itself, or in totally quiescent water. They would do it because of their own inherent kinetic energy.

Referring to Figure 1, all molecules possess inherent kinetic energy associated with their surrounding temperature, the average kinetic energy being just 3/2 kT, where k is the Boltzmann Constant and T is the absolute temperature. In terms of mass and velocity, molecules of a specific mass will move about with a specific velocity, on the average, according to the model $KE = 1/2\ mv^2$. The dissolved molecules therefore move about more or less as shown by the arrows in Figure 1, and this motion is entirely random and takes place in random directions. It is this movement due to inherent kinetic energy that allows the dissolved molecules to spread out and eventually achieve uniform concentration in the beaker of water, by molecular diffusion.

Fick's first law of diffusion places molecular diffusion on a quantitative basis. Referring to Figure 1, J is the net flux of molecules (in $mg/cm^2/sec$) across any plane within the volume of water; $\frac{dc}{dr}$ refers to the concentration gradient across the plane (dc represents the difference in concentration of dissolved material on the two sides of the plane, and dr represents the infinitesimal distance from one side of the plane to the other), and is the driving force for diffusion; D_m is referred to as the coefficient of molecular diffusion,

$\overline{KE} = \frac{3}{2} kT$

Fick's First Law:

$$J = -D_m \frac{dc}{dr}$$

$$(mg/cm^2/sec) = (cm^2/sec) \times (\frac{mg/cm^3}{cm})$$

$$D_m = \frac{RT}{N_o f} \qquad \text{(Einstein)}$$

$$f = 6\pi\eta r \qquad \text{(Stokes)}$$

Hence,

$$D_m = f(T, \eta, r)$$

and

$\frac{dc}{dr}$ = driving force for diffusion

FIGURE 1

MOLECULAR DIFFUSION

and its magnitude depends upon the molecular characteristics of both the diffusing molecules and the surrounding medium.

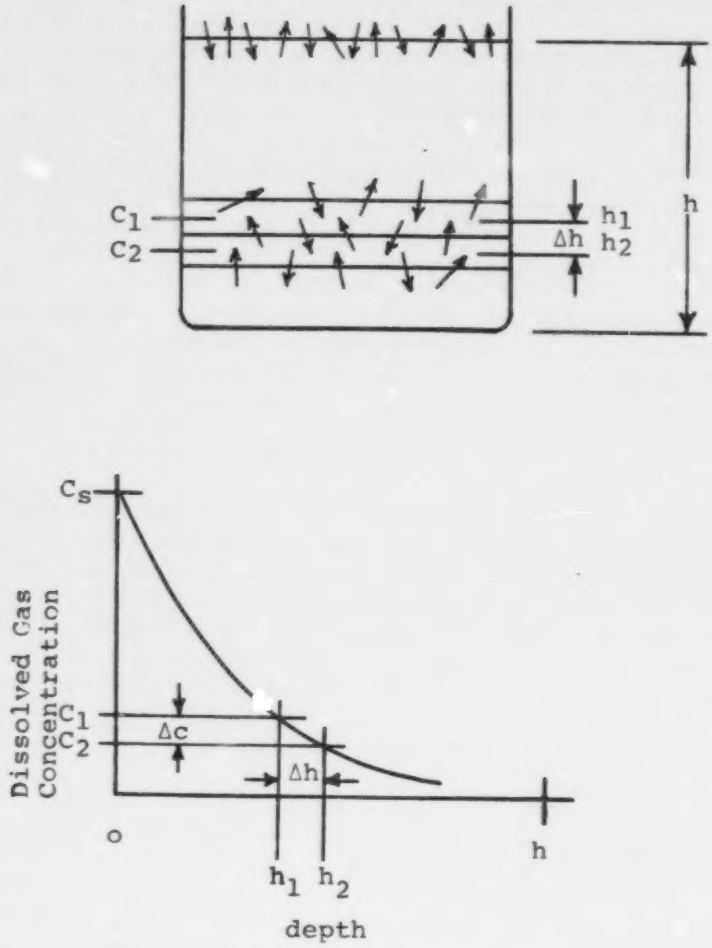
In 1905, Albert Einstein developed an equation for evaluation of the molecular diffusion coefficient, based upon his studies of the Brownian motion. Referring to Figure 1, the diffusion coefficient, D_m, is seen to be equal to the product of the universal gas constant, R, and the absolute temperature, T, divided by Avogadro's number, N_o, and a "friction factor", f, related to the ability of the surrounding medium to impede the progress of the diffusing molecule.

A little later, Stokes further defined the friction factor, f, for spherical particles falling freely through water, and showed the friction factor to be directly proportional to the viscosity, η, of the medium and the radius, r, of the falling sphere. Hence, the diffusion coefficient, D_m, is seen to be a function of the absolute temperature, the viscosity of the fluid and the size of the diffusing particle.

Now a word about gas molecules, and regarding them as spheres. If we could take a single oxygen molecule and set it down on a table, and hold it still, it would not look like a sphere. Presumably, this diatomic molecule might look something like a dumbbell. However, one cannot set it down on a table and hold it still long enough to look at it, because this single molecule is constantly in motion. First, it has what we call "spin", and it spins like a top about an axis; secondly, the axis itself "precesses", as though the top were wobbling, about some other axis; thirdly, the molecule possesses "dipole moments" and "quadrupole moments" related to the movement of the atoms with respect to each other. The combined effect of all of these motions is to make the molecule behave like a sphere, even though it wouldn't look like one if it could sit still on a table. Nor will the effective diameter of the operating sphere be the same as the length of the quiet dumbbell. The effective diameter of the spherical gas molecule is of the order of angstrom units (1 angstrom = 10^{-8}cm).

To summarize, then, molecular diffusion takes place because of the inherent kinetic energy of the diffusing molecules and in proportion to the magnitude of the existing concentration gradient; the diffusion coefficient is a function of the absolute temperature, the viscosity of the fluid medium and the size of the diffusing molecules.

Figure 2 illustrates the mechanics of gas transfer in completely quiescent water. The water is completely still, there being no temperature gradients, convection currents, or other motion of volume elements of water. (Although such a


C1
C2
h1
Δh
h2
h
Cs
Dissolved Gas Concentration
C1
C2
Δc
Δh
o
h
h1
h2
depth

$(C_1 - C_2) = \Delta C = \text{very small}$

$\therefore (\frac{\Delta C}{\Delta h}) = \text{very small}$

$\therefore J \cong - D_m (\frac{\Delta C}{\Delta h}) = \text{very small}$

FIGURE 2

GAS TRANSFER IN STAGNANT WATER

system might well be impossible to achieve experimentally, the concept is valid and suitable for our purposes here). Initially, there is no dissolved oxygen at all in the water, so that initially oxygen molecules move only into the water from the overlying atmosphere.

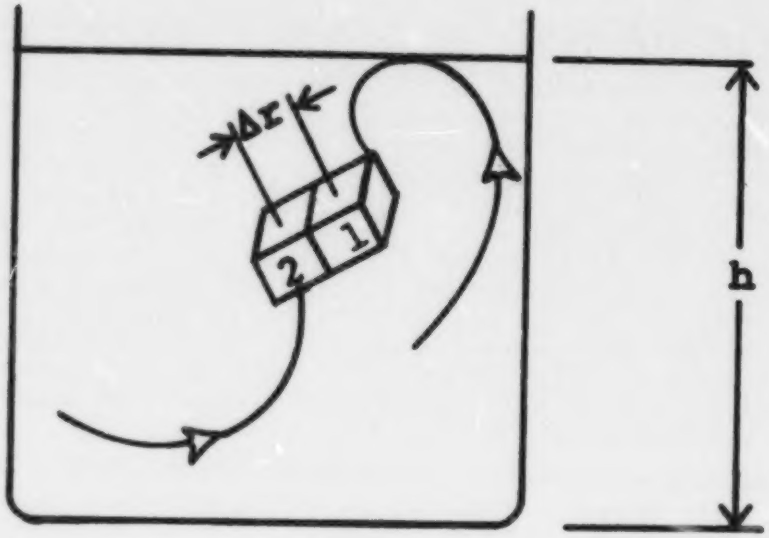
A little later, there will be available dissolved oxygen molecules in the upper water layer near the water surface; they also are in constant movement due to their inherent kinetic energy, and they move in random directions. Some of them escape again to the overlying atmosphere, while others diffuse to deeper water layers. However, oxygen molecules are able to enter the topmost water layer from the overlying atmosphere more easily than they are able to diffuse downward through the fluid medium. As a result, the dissolved gas molecules accumulate fairly rapidly in the uppermost water layers, and those layers become "saturated."

At any time after the start of the experiment, the net rate of entry of gas molecules at the air-water interface is just the rate of entry from above (constant, because the overlying atmosphere has constant oxygen concentration) minus the rate of escape back to the atmosphere (proportional to the dissolved oxygen concentration in the uppermost water layer). As a result of the relatively rapid accumulation of gas molecules in the topmost water layer, the net rate of entry (or, reaeration) soon becomes very small.

As a result, the deeper water layers soon become "starved" for oxygen molecules. Referring to Figure 2, across any infinitesimal distance (depth) Δh, the dissolved oxygen concentration difference, $\Delta C = (C_1 - C_2)$, is infinitesimally small. Hence, at any depth and at any time, the driving force for molecular diffusion, the concentration gradient $(\frac{\Delta C}{\Delta h})$, is very small. Referring back, then, to Fick's law, diffusion of oxygen molecules downward is very slow, and reaeration of truly stagnant water is a very slow process that requires days or weeks before the bottom layers of water approach DO saturation. The whole process is slow because of the blocking action of molecular diffusion.

TURBULENT MIXING

Consider now the same beaker of water, but no longer quiescent. Instead, the water is being mixed by some external force (perhaps the beaker is being stirred, or is sitting on a vibrating platform). We will be concerned now primarily with volume elements of water, rather than with molecules of oxygen. We define a volume element to be infinitesimally



$$(C_1 - C_2) = \Delta C = \text{large}$$

$$\therefore \left(\frac{\Delta C}{\Delta r}\right) = \text{large}$$

$$\therefore J \cong - D_m \frac{\Delta C}{\Delta r} = \text{large}$$

FIGURE 3

GAS TRANSFER IN TURBULENT WATER

small in the calculus sense, but large enough to contain a very large number of molecules.

Referring to Figure 3, at the start of our experiment the water contains no dissolved oxygen. Volume element No. 1 moves up to the water surface from below and remains there for a definite, if very small, period of time. Because it contained no dissolved oxygen, the net rate of entry of gas molecules from the overlying atmosphere is very large - at a maximum - and the volume element gains a relatively large amount of dissolved oxygen before it leaves the surface to move downward to a deeper location. In its downward path it encounters a second volume element of water, No. 2, that has never been at the water surface and so contains very little or no dissolved oxygen. Thus, the one volume element contains quite a large amount of dissolved oxygen compared to the other, and at the interface between them there is a large concentration difference, $\Delta C = (C_1 - C_2)$. Hence, for that moment across that interface, the driving force for molecular diffusion, $(\frac{\Delta C}{\Delta r})$, is relatively large, and the transfer of dissolved gas molecules from the one volume element to the other is relatively rapid.

If we now multiply this example by all of the volume elements of water in the beaker, it is clear that mixing greatly speeds the reaeration process. The water surface is constantly replaced by volume elements from below, and hence the blocking action of molecular diffusion is no longer present. The lower water depths are no more starved for dissolved oxygen than the upper locations. The average concentration of dissolved oxygen is at any time the same at all depths and all locations, including the surface, in a homogeneously mixed system, and, hence, the net rate of entry of gas molecules at the water surface remains relatively large until the whole volume of water approaches the DO saturation concentration. Note also that the dissolved oxygen concentration gradient does not now occur in any preferred direction, such as downward. Instead, there is an average concentration gradient throughout the whole volume of water, and it is multidirectional.

It is also clear that the faster the water is mixed, and the surface replaced, the faster will be the reaeration process. Instead of days or longer, the water can be saturated with dissolved oxygen in minutes at high rates of mix. Thus, molecular diffusion keeps up with mixing in the turbulent system, instead of blocking reaeration. It is also important to note that in the mixed system the depth of water has nothing to do with the rate of reaeration except insofar as the depth-to-volume ratio influences the physical rate of water surface replacement.

So far as reaeration is concerned, then, the term "turbulence" has a special meaning relating strictly to the rate of water surface replacement and to the dispersion of volume elements of water. Turbulent mixing of the water and consequent dispersion of the dissolved gas molecules takes place due to the application of external forces, such as the platform vibration, or a mechanical stirrer, etc. It enhances molecular diffusion and reaeration as outlined above.

Misconceptions. The foregoing outline of the fundamental mechanisms of gas transfer in turbulent water systems indicates that certain widely held concepts of gas transfer are not, in fact, correct representations of the physical facts. In the first place, in a well-mixed system, or in a turbulent natural stream, the surface water layer is not saturated with dissolved oxygen - constant surface replacement precludes this. Also, as indicated above, there is no preferred direction of oxygen transfer, such as downward, and the physical depth of a water-course influences reaeration only to the extent that it influences the rate of water surface replacement in the hydraulic sense.

In particular, in a homogeneously mixed system no stagnant surface water "film" can exist for any finite period of time, and, hence, even though it may be an adequate mathematical convenience in some situations, the "film theory" of gas transfer is wrong in concept. The film theory denies the obvious fact of physical surface water replacement, and is based upon the false supposition that a dissolved oxygen concentration gradient is not present within a well-mixed system - as has been seen, such a concentration gradient is the driving force for diffusion, and it exists everywhere within the unsaturated fluid volume.

A clear distinction must therefore also be made between physically impossible stagnant surface water films and physically real hydrodynamic upper layers of water in a system that is not homogeneously mixed. For example, in a stratified reservoir the whole volume of water is physically or hydrodynamically separated into two distinct regions - the lower region has little opportunity for reaeration because its volume elements never reach the air-water interface. In that case, then, the hydrodynamic situation prevents surface replacement and reaeration is very slow. However, this has to do with the hydraulic properties of the system, and has nothing to do with the film theory.

MATHEMATICAL RELATIONSHIPS

Based upon the foregoing considerations of molecular diffusion and turbulent mixing, the following mathematical relationships have been derived and demonstrated experimentally. The relationships are simply reproduced here, the reader being referred to the detailed 1967 FWPCA report for the derivations and the supporting experimental evidence.[10]

Referring to the definitions given earlier, for a turbulent water system we can write

$$D = (C_s - C) \tag{1}$$

where D is the saturation deficit, C_s is the saturation limit, and C is the momentary average DO, all expressed as mg/l of water.

The familiar basic reaeration equation has been derived elsewhere from simple first principles[10]

$$\frac{dD}{dt} = -K_2 D \tag{2}$$

and states simply that the rate of change of the saturation deficit (the driving force) at any time is proportional to the deficit at that time, or, the greater the saturation deficit the greater the rate of reaeration. The proportionality constant, K_2, is the "reaeration rate coefficient" for the specific set of conditions, and its numerical magnitude depends, in particular, upon the degree of turbulent mixing of the water.

Equation (2) is solved by

$$D = D_o e^{-K_2 t} \tag{3}$$

where D_o is the initial dissolved oxygen deficit (at $t = 0$).

It has also been shown elsewhere[10] that

$$K_2 = a\ n\ \frac{A}{V} \tag{4}$$

in a turbulent water system, which states that the reaeration rate coefficient, K_2, is directly proportional to the rate of surface replacement. In equation (4), A is the exposed surface area of water in cm^2, V is the whole volume of water in

cm^3 and n is the number of new surfaces exposed per unit time. Thus the product $(n\frac{A}{V})$ is just the area of new surface exposed in cm^2 per unit time and per unit volume. The proportionality constant, a, is directly related to the coefficient of molecular diffusion, D_m, and is therefore a function only of the molecular properties of the dissolved gas and the physical properties of the water. The coefficient, a, is thus a constant for oxygen in clean water at any fixed temperature, but it will be a function of the water temperature and it may also be modified by the presence of pollutants. It is not a function of the degree of turbulence.

It should be noted that the quotient (A/V) is properly regarded as the reciprocal of the whole depth of water only under conditions of complete homogeneous mixing. Thus, for example, the whole depth of water in a stratified reservoir is meaningless as a measure of K_2 or reaeration capacity. In point of fact, it is probable that many natural watercourses, especially large slow-moving rivers, are not homogeneously mixed, and in such cases the average depth of flow is not a measure of the depth that is effective in terms of surface replacement or reaeration.

With appropriate modification, the foregoing expressions also describe the absorption or desorption of other gases. Specifically, consider a dissolved tracer gas, krypton-85 which has been added to the water. The amount of krypton-85 present in the atmosphere above the water can be taken to be zero, for practical purposes. Hence, the driving force for gas transfer will be just the partial pressure of the dissolved krypton-85 in the water, transfer will be from the water to the atmosphere, and the tracer gas will be steadily lost from the water.

Thus, in the case of desorption of the tracer gas we can write

$$C = C_o e^{-K_2 t} \tag{5}$$

where C is the concentration of the dissolved tracer gas remaining in the water at time, t, C_o is the concentration at t = 0, and K_2 is the gas transfer coefficient for the tracer gas.

(At this point, in order to avoid confusion, we will no longer use the subscript "2" to denote reaeration or gas transfer. Instead, the constant K will represent the gas transfer coefficient for any gas, including oxygen, and the subscript used will identify the specific gas. For instance,

"K_{ox}" will be understood to mean the K_2 value for oxygen, and "K_{kr}" will identify the K_2 value for krypton, etc.).

As has been shown in the earlier work[10], different gases have different transfer coefficients because of the different molecular characteristics of the gases. Thus, referring to equation (4), the numerical value of the constant, a, will be different for different gases, under identical hydraulic conditions. In an extended series of experiments involving a number of different gases (hydrogen, helium, nitrogen, carbon dioxide, oxygen, radon and krypton), and also on theoretical grounds, it has been demonstrated that for any pair of different gases

$$\left(\frac{K_A}{K_B}\right) = \left(\frac{D_{mA}}{D_{mB}}\right) = \left(\frac{d_B}{d_A}\right) \qquad (6)$$

Equation (6) states that the ratio of gas transfer coefficients for two different gases is just equal to the ratio of molecular diffusivities, and that both ratios are equal to the inverse ratio of their molecular sizes, under identical conditions of turbulent mixing. In other terms, the larger the gas molecule, the lower its relative gas transfer ability.

It has thus been shown, both experimentally and theoretically, that for the same conditions of turbulence

$$\left(\frac{K_{kr}}{K_{ox}}\right) = 0.83 \pm 0.04 \qquad (7)$$

and this provides the necessary basis for the use of krypton-85 as a tracer for dissolved oxygen in stream studies.

It should also be noted that the numerical constant, 0.83, given in equation (7) has been demonstrated to be independent of the degree of turbulent mixing, independent of the directions in which the two gases happen to be moving, and independent of temperature within the range 10 to 30°C.

Although the ratio of transfer coefficients for two different gases is independent of temperature for practical purposes within the temperature range of interest, it has long been recognized that the magnitudes of the individual coefficients are affected by water temperature. Specifically, the numerical magnitude of any value of K increases with increasing temperature, and vice versa. Also, for any gas, the saturation limit decreases with increasing temperature, and vice versa. The exact magnitude of the temperature effect on K has remained a subject of considerable controversy until quite recently.

It has been shown in the earlier FWPCA report[10] that on theoretical grounds

$$\frac{K(T_2)}{K(T_1)} = \frac{C_s(T_1)}{C_s(T_2)} \tag{8}$$

where T_1 and T_2 are two different water temperatures, $K(T_1)$ and $K(T_2)$ are the respective values of K, and $C_s(T_1)$ and $C_s(T_2)$ are the respective values of the saturation limit. Combining equation (8) with the usual expression for the temperature effect on K

$$\frac{K(T_2)}{K(T_1)} = \frac{C_s(T_1)}{C_s(T_2)} = \theta^{(T_2 - T_1)} \tag{9}$$

where θ is the commonly applied temperature coefficient.

Using the known dissolved oxygen saturation concentrations in clean water at standard atmospheric pressure for temperatures from 0°C to 30°C,[12] it has been found that

$$\theta_{mean} = 1.022 \pm 0.004 \tag{10}$$

Exactly the same value was found for water containing large quantities of chlorides[10].

The foregoing predicted mean value for θ of 1.022 agrees excellently with the value of 1.024 observed experimentally by Churchill et al[5]. From this combination of theory[10], experimentally determined values of C_s[12], and experimentally observed values of θ[5], the value $\theta = 1.022 \pm 0.004$ is taken to be firmly established.

FIELD TRACER APPLICATION

The mathematical basis of the field tracer technique for determining the reaeration rate coefficient, K_{OX}, in natural streams has been outlined in detail in earlier publications[9, 10], but is also summarized here for the sake of completeness and immediate reference.

Let A and B represent two points along the course of a stream, with A being the upstream location, and let a quantity of dissolved krypton-85 be introduced at a location upstream from A. If this tracer dose could be introduced in such a way as to be uniform in concentration across the stream section, and if we then collected samples from A and B at the moment of maximum tracer concentration at each location and analyzed these samples for krypton-85, then the numerical value of K_{kr} for the reach (AB) could be obtained directly by the use of equation (5):

$$\left(\frac{C_B}{C_A}\right) = e^{-K_{kr}t}$$

where C_A and C_B are the maximum dissolved krypton-85 concentrations at A and B, t is the time of flow between A and B, and the ratio (C_B/C_A) is just the decimal fraction of tracer gas remaining at point B. The reaeration rate coefficient, K_{ox}, for that reach could then be obtained directly from equation (7).

In practice, it is not really possible to achieve a truly uniform cross-sectional tracer dose. Also, if we only use the dissolved tracer gas, we have no way of knowing exactly when the maximum concentration occurs at A and B. However, these problems may be solved by the use of additional tracers.

In brief, the field application involves the simultaneous release of a homogeneous mixture of three tracers. This tracer dose is essentially instantaneous, and can be a point dose in the stream cross-section. The three tracers are dissolved krypton-85, tritium in the form of tritiated water molecules, and a fluorescent dye. At downstream sampling locations the dye concentration is monitored continuously by the use of a continuous flow recording fluorometer, and suitable samples of river water are collected at frequent intervals as the peak dye concentration approaches and passes the sampling point. Samples representative of the maximum dye concentration are subsequently analyzed for tritium and krypton-85.

The fluorescent dye performs two functions: it indicates when to sample for the two invisible radioactive tracers, and it provides an accurate measure of the time of flow between sampling stations. The tritiated water provides an accurate measure of dispersion of the tracer dose: the concentration of tritium decreases between sampling locations because the tracer is dispersed as the result of longitudinal, lateral and vertical mixing, and, being in the form of water molecules, tritium is not adsorbed on the stream bed or otherwise lost in any significant amount. Because the three tracers were released simultaneously, the dissolved krypton-85 undergoes exactly the same dispersion as the tritiated water; in addition, it is lost to the atmosphere according to the foregoing models, but, being chemically inert, it suffers no other losses of any significance.

Under these test conditions, the observed concentrations of tritium provide an accurate correction for the effects of dispersion, and hence the decimal fraction of tracer gas remaining at point B is just

$$\frac{\left(\frac{C_{kr}}{C_{tr}}\right)_B}{\left(\frac{C_{kr}}{C_{tr}}\right)_A} = e^{-K_{kr}t} \qquad (11)$$

where $(C_{kr}/C_{tr})_{A,B}$ are the concentration ratios of krypton-85 and tritium in the samples taken at the time of the dye peaks at A and B, and t is the time of flow between the two locations. Hence, an accurate evaluation of K_{kr} can be made for any such reach of stream, and the conversion to a K_{ox} can then be made using equation (7).

The krypton-85 and tritium concentrations in the river water samples are measured by a liquid scintillation counting technique, for maximum counting efficiency. The tracer doses are quite small in relation to permissible environmental limits, and the exposure of personnel handling the tracer dose is minimal and controllable. The field and laboratory procedures have been described in detail in earlier publications[9, 10].

As indicated earlier, although the ratio of gas transfer coefficients, (K_{kr}/K_{ox}), is not affected by water temperature in the range of interest, the individual coefficients are affected. Hence, for comparing values of K_{ox} in different streams, and for seeking relationships between K_{ox} and stream hydraulic properties, the field-determined values of K_{ox} are converted to a common temperature by the use of equations (9) and (10).

AVERAGE NATURE OF K

The available procedures for estimating the reaeration capacity of natural streams generally require the assumption of uniform mixing and turbulence over relatively long stream reaches. In particular, they treat reaeration as a single first-order process over substantial distances, as no other practical alternative has been available. Cautiously applied, this approach does not necessarily lead to large error in estimates of the reaeration capacity. However, it is decidedly an averaging procedure, rather than an exact one, as the actual reaeration rate coefficient, like the actual rate of water surface replacement, undoubtedly varies substantially within most such river reaches. As will be seen in the subsequent discussion of Experimental Results, in many streams most of the real action of gas transfer takes place in short times of flow.

The tracer method described here and applied in this research requires no such assumptions as to uniformity of mixing or turbulence, or constancy of the reaeration coefficient. It provides a direct and quite independent measure of the gas exchange capacity under existing conditions of mixing and surface water replacement, whatever they may be.

PREDICTIVE MODELS

A number of theoretical and empirical models for the reaeration coefficient have been proposed. A recent publication[11] resulting from a literature search and a state-of-the-art review on the topic of reaeration of streams and reservoirs includes a discussion of many of these models. In addition, in an earlier report on the use of tracers for the measurement of reaeration[10] several of the models in current use were discussed. With these more detailed accounts of previous investigations readily available, it is not necessary to again present a complete analysis of the models previously developed. However, a comparison between the values of k_2 predicted by several of these models and values determined by the tracer method is included in one of the following sections of this report, and for this reason outlines of several of these models are presented below.

Streeter and Phelps[2]. One of the earliest models of stream self-purification was developed by Streeter and Phelps from data collected on the Ohio River. These authors reasoned that the rate of reaeration is influenced by the hydraulic characteristics of the stream. Their model combined the concepts of molecular diffusion and turbulence. It had been shown earlier in a model developed by Black and Phelps[1] that when the reaeration process is governed solely by molecular diffusion the reaeration rate coefficient is inversely proportional to the square of the depth. To this model Streeter and Phelps added their concept of the relation between turbulence and stream velocity. They stated that "under uniform physical conditions [turbulence] might be expected to be a power function of the velocity of the form:

$$T = cV^n \qquad (12)$$

the constants c and n defining the stream type as regards the fixed physical conditions, such as slope, character of the bottom, depth, shape, and direction of channel, etc." By combining these concepts they formulated the empirical model

$$K_2 = \frac{cV^n}{H^2} \qquad (13)$$

where H is the depth, V the velocity of flow, and c and n are constants that must be evaluated empirically for any specific stream section. Streeter and Phelps evaluated these constants by an indirect method on a number of reaches of the Ohio River. This process required the estimation of the magnitude of the effect of each of the stream phenomena that influence the concentration of dissolved oxygen, and the subsequent insertion of these values into the oxygen sag equation from which the value of K_2 was then computed. Mean values of n determined in this manner ranged from 0.57 to 5.40, while the values of c varied from 0.23 to 131. These investigators suggested that such wide variations in these coefficients are to be expected and that further studies would doubtlessly disclose that all streams would not follow their model for K_2.

O'Connor and Dobbins.[4] In 1958 O'Connor and Dobbins, working with the idealized oxygen sag equation developed and used by Streeter and Phelps, developed models for the reaeration coefficient which were based on certain theoretical concepts from the field of fluid turbulence and on assumed relationships defining the rate of surface renewal. Two flow categories were specified and an equation was developed for each category. The equation

$$k_2 = \frac{480\ D_L^{1/2}\ S^{1/4}}{H^{5/4}} \qquad (14)$$

was suggested for use in streams characterized by non-isotropic turbulence. In this model S is the slope of the stream channel, D_L is the coefficient of molecular diffusivity, and H is the average depth. For streams in which turbulence approaches an isotropic condition, O'Connor and Dobbins approximated the reaeration coefficient by the relationship

$$k_2 = \frac{D_L^{1/2} V^{1/2}}{2.31\ H^{3/2}} \tag{15}$$

where V is the mean velocity of flow.

The verification of these models was based on both field and laboratory data. The laboratory data were generated by an apparatus consisting of a lattice work moving in simple harmonic motion in a 5 1/2-inch diameter cylinder containing approximately 2,500 ml. of water. The field data were selected from results collected by other earlier investigators, who computed k_2 values for the various streams by the indirect method. Much of the field data on hydraulic characteristics which pertained to these earlier investigations was not in the form required by the O'Connor-Dobbins model, and it was necessary for O'Connor and Dobbins to make some rather rough estimates regarding such variables as mean velocity and depth of flow. These authors reported good agreement between the coefficients calculated by others from earlier river surveys and those calculated by the O'Connor-Dobbins formulae. In addition, O'Connor and Dobbins were of the opinion that their laboratory experiments substantiated their theoretical developments.

Krenkel and Orlob.[6] The importance of various factors in the reaeration process were discussed by Krenkel and Orlob. Conclusions were drawn regarding the effects of oxygen deficit, area-to-volume ratio, time of exposure of water elements at the free surface, temperature, partial pressure of solute gas, molecular diffusivity, energy dissipation and turbulent diffusion. They suggested that the overall mixing characteristics of a stream section are reflected in a "longitudinal mixing coefficient," D_L,defined by the equation

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - \bar{u} \frac{\partial c}{\partial x} \tag{16}$$

where c is the concentration of a tracer injected into a stream, t is time, x is distance along the stream and $\bar{u}$ is the mean stream velocity.

Experiments were conducted in a laboratory flume in order to examine the relationship between k_2 and D_L. Oxygen was first removed from the water by the addition of sodium sulfite, and the reaeration rate coefficient was determined by measuring the concentration profile of a tracer material which affected the conductivity of the water.

After correcting all test values to a constant temperature of 20°C it was found that the temperature adjusted values of the reaeration coefficient k_2[1] could be fitted best by a regression equation of the following form

$$k_2(20°C) = (1.138 \times 10^{-5})\ D_L^{1.321}\ H^{-2.32} \tag{17}$$

in which H is the average depth. In addition, Krenkel and Orlob stated that they expected to find the reaeration coefficient to be directly proportional to the energy expenditure per unit mass of fluid and that some measure of the size of turbulent eddies should be effective in the reaeration process. They hypothesized a relation of the form

$$k_2(20°C) = (\text{constant})\ E^b H^c \tag{18}$$

where E is the energy dissipation per unit mass of fluid, computed from the relation

$$E = \bar{u}\ S\ g \tag{19}$$

in which S is the slope of the energy gradient, g is the gravitational constant, and $\bar{u}$ is the mean stream velocity. The constants were evaluated by fitting the flume data, and the resulting equation was

$$k_2(20°C) = (1.141 \times 10^{-4})\ E^{0.408}\ H^{-0.660} \tag{20}$$

Churchill, Elmore and Buckingham.[5] Perhaps the most comprehensive empirical study of the reaeration process was conducted by Churchill, Elmore and Buckingham on several tributary streams in the upper Tennessee River basin. Many of the difficulties which hindered earlier field studies were minimized by careful selection of the study reaches and by carrying out all measurements during periods of controlled releases from upstream dams. Dimensional analysis and multiple regression techniques were applied to analyze the data. Variables included in the regression analysis were flow, velocity, mean depth, energy slope, resistance coefficient, fluid density, fluid viscosity, surface tension, molecular diffusion coefficient, and a vertical diffusion coefficient.

Nineteen different combinations of these variables were analyzed, and the nineteen equations which resulted were presented and discussed. The recommended equation had the form

$$k_2(20°C) = 5.026\ V^{0.969}\ H^{-1.673} \tag{21}$$

where V is the mean stream velocity and H is the mean depth. The coefficient of multiple correlation for this equation, as determined by the data collected by Churchill et al., was 0.822, while the correlation coefficients for the other eighteen equations ranged from a low of 0.805 to a high of 0.846. Thus, any one of the nineteen equations developed by Churchill, Elmore, and Buckingham is essentially as good a predictor as any other. Since there was no significant improvement in the equations when terms other than V and H were used, it was suggested that the equation

$$k_2(20°C) = 5\ V\ H^{-5/3} \tag{22}$$

be used, and that the simplification of the constants in this form, as compared to the values in the regression equation, would not significantly affect the predictions in most applications.

Churchill's data have been used by several investigators for the development of additional models of k_2. Isaacs and Maag[13] employed these data to evaluate a model of a form similar to that recommended by Churchill. Their equation is

$$k_2 = C\ \phi_s \phi_v\ \frac{V}{H^{3/2}} \tag{23}$$

where V = mean stream velocity, H = mean depth, C = constant, ϕ_s = a non-dimensional variable which varies with the channel geometry, and ϕ_v = a non-dimensional variable which is a measure of the surface velocity. The coefficient for channel shape was added by Isaacs and Maag because they believed the deviations observed between field and laboratory measurements of the reaeration coefficient possibly represented the departure in the field from the constant prismatic channel section used in the laboratory studies. In addition, they noted that most theories describing the reaeration process consider conditions at the stream surface to be highly important. Based on their use of Churchill's data an equation of the form

$$k_2 = 2.98\, \phi_s \phi_v \frac{V}{H^{3/2}} \tag{24}$$

was recommended. The average value of ϕ_s was found to be 1.078 and the average for ϕ_v was 1.16. A correlation coefficient of 0.989 was reported.

Langbein and Durum[14] used Churchill's field data together with the field data collected by others (such as by Streeter and Phelps) and reported by O'Connor and Dobbins, plus the laboratory data of Krenkel and Orlob and Streeter, Wright, and Kehr[15]. These data, when plotted on the same graph, indicated that an equation of the form

$$k_2 = 3.3\, V H^{-1.33} \tag{25}$$

would accommodate both the laboratory and field data. The failure of Langbein and Durum to include all of Churchill's data in their analysis was pointed out by Isaacs and Maag[13].

Owens, Edwards, and Gibbs[16] also used data collected by Churchill as well as the field data of Gameson, Truesdale, and Downing[17] and by regression analysis arrived at the equation

$$k_2\ (20°\mathrm{C}) = 9.41\, V^{0.67} H^{-1.85} \tag{26}$$

where U is the mean velocity and H is the mean depth.

Thackston and Krenkel[7]. The basic premise adopted by Thackston and Krenkel is one that was originally proposed by Krenkel[18], i.e., that k_2 is proportional to k_y/H^2 where k_y is the vertical mass transfer coefficient and H is the depth of flow. In their paper they derive an expression for k_y based on the mechanics of open channel flow. An outline of the steps followed by Thackston and Krenkel to estimate the vertical mass transfer coefficient is presented in the following paragraph.

The mean transfer coefficient was assumed to be proportional to the momentum transfer coefficient ε_y defined by

$$\tau = \varepsilon_y \frac{d(\rho u)}{dy} \tag{27}$$

where τ is the fluid shear stress, ρ is the density, and u the local velocity at depth y. Measurements[19] of k_y and ε_y in the laboratory showed that neither ε_y nor k_y become zero at the free surface although a zero value is predicted by the use of von Karman's logarithmic velocity distribution. The variation of both of these values with depth was shown experimentally to be almost identical. The variation of ε_y in the vertical direction was shown to follow quite closely a relation based on Vanoni's modification of the von Karman universal velocity distribution. This relation is

$$\varepsilon_y = K\, u_* \, y \left(1 - \frac{y}{H}\right) \tag{28}$$

where K is the von Karman coefficient, U_* is the shear velocity, and y is the vertical coordinate. Thus, from equation (28) the average value of ε_y is $(K/6)\ H\ U_*$.

If it is assumed that the value of k_y is proportional to the value of ε_y at any value of the relative depth y/H, then it follows that the value of k_y at the surface is

$$k_y = C_1 \frac{K}{6} H\ u_* = C_2\ H\ u_* \tag{29}$$

Returning to the basic assumption of Thackston and Krenkel, i.e., that

$$k_2 \propto \frac{k_y}{H^2} \tag{30}$$

then the equation for k_2 becomes

$$k_2 = \frac{C_4\ C_2\ H\ u_*}{H^2} = C_5\ \frac{u_*}{H} \tag{31}$$

where the constant C_5 must be evaluated experimentally. Equation (31) is the basic equation developed by Thackston and

Krenkel. The constant was evaluated from laboratory data, and when substituted in equation (31) yields

$$k_2 = 0.000215 \frac{u_*}{H} \tag{32}$$

where u_* is computed from

$$u_* = (HSg)^{1/2} \tag{33}$$

In order to account for the difference between the actual area of the air-water interface and the projected area, another term was added to equation (20). Because the Froude number is an indicator of the roughness of the water surface, it was incorporated into equation (31) and the constant was then reevaluated. The final form of the equation was then

$$k_2 = 0.000125 \, (1 + F^{1/2}) \, \frac{u_*}{H} \tag{34}$$

where F is the Froude number, $V/(gH)^{1/2}$. Thackston and Krenkel point out that their equation is insensitive to errors in velocity, and relatively less sensitive to depth than many of the previously formulated models.

Summary. With few exceptions, the currently available predictive models for the reaeration coefficient follow the form proposed by Streeter and Phelps some 46 years ago[2]. Thus, the models proposed by O'Connor and Dobbins[4], Langbein and Durum[14], Owens et al[16], and Churchill et al[5] are all identical in form with the original Streeter-Phelps model, and all of these models differ among themselves only in terms of the numerical values of empirical coefficients. As indicated so clearly by Streeter and Phelps, wide variation of the empirical coefficients is to be expected. The Isaacs-Maag model[13] contains an additional empirical factor for channel shape, but remains identical to the others in form.

Krenkel and Orlob[6] attempted to explain reaeration in terms of a longitudinal mixing coefficient, and provided an additional model in which the slope of the energy gradient was added to the Streeter-Phelps form. Later, Thackston and Krenkel[7] provided a modified form involving the Froude Number.

The main source of difficulty in all of the foregoing efforts to develop an adequate predictive model for K_2 has been the lack of independently observed accurate values of K_2 in natural streams, for purposes of model testing. Only Streeter and Phelps and Churchill et al conducted extensive field studies to obtain values of K_2 by indirect oxygen balance. Some of the subsequently proposed models, e.g., those of O'Connor and Dobbins, Langbein and Durum and Isaacs and Maag, have been based completely upon the values of K_2 obtained by others.

The studies of Churchill et al are the most extensive and thorough of recent times. As noted earlier, these investigators attempted to relate reaeration capacity to hydraulic properties by means of nineteen different models involving some eight to ten hydraulic properties. All of the models produced very similar correlation coefficients. These studies have demonstrated beyond further question that, in such attempts, the magnitude of a correlation coefficient does not, in itself, constitute adequate or sufficient evidence of the real usefulness of any particular empirical model. Recognizing this, Churchill advised general use of the simplest of his models, which had about the same correlation coefficient as the others.

SECTION V

EXPERIMENTAL PROCEDURES

This section of the report includes a summary of the experimental procedures that were used in the several research areas, field and laboratory. This includes the field studies of the physical and hydraulic properties of the Flint, South and Chattahoochee Rivers, the field tracer studies of the reaeration capacity of those streams, the associated DO and BOD studies, and the studies of the effects of pollutants on the reaeration capacity. Details of the various field and laboratory procedures are provided to the extent necessary for a full description of the research performed. Where appropriate, the reader is referred to earlier published details of analytical and other procedures.

Descriptions of the streams studied, with maps and relevant detail such as sampling stations, are provided in Section VI-Experimental Results. In general, river sampling stations were selected both for relevance to specific hydraulic features and for accessibility.

PHYSICAL AND HYDRAULIC PROPERTIES

Measurements of hydraulic properties were made at stations located at 500-foot intervals along the South River, Flint River and Chattahoochee River. Data were obtained for computing channel slope, cross sectional area, stream width, depth, hydraulic radius, velocity, and discharge. Distances were measured along the main channel of the stream with a steel tagline, and a stake was driven into the bank and marked with a station number at the end of each 500-foot interval. Levels were run to the top of each stake and to the water surface opposite the stakes. The levels were run using standard leveling procedures and the work was checked by tying the levels to bench marks located on highway bridges. Bench mark elevations were obtained from the US Corps of Engineers, the US Geological Survey, the State Highway Department of Georgia, and from the Offices of Public Works of Fulton and DeKalb Counties.

Standard US Geological Survey stream gaging techniques, with slight modifications, were employed by the field crew. Width of cross section was measured with a tagline or steel tape, and depths and velocities on the Flint and South Rivers were measured with a top-setting wading rod and Price current meter. The procedures followed for the hydraulic studies on the Chattahoochee River were identical to those on the smaller rivers with the exception that measurements were made from a boat rather than by wading the stream. The field crew measured an average of thirteen depths and velocities at each cross section on the smaller streams and on the Chattahoochee; all velocities were measured at six-tenths of the depth.

Typical cross section notes are shown in Figure 4. The discharge, velocity and geometric properties of each cross section were determined from these notes. The computation of cross-sectional area and discharge are also illustrated in the typical notes of Figure 4. The values of "distance from initial point" and "depth" for each cross section were punched on computer cards for additional processing. The wetted perimeter was computed from the relationship

$$P = \sum \left[(X_{i+1} - x_i)^2 + (d_{i+1} - d_i)^2 \right]^{1/2} \qquad (35)$$

where x_i is the distance from the initial point on the stream bank to the i^{th} depth measurement, and d_i is the depth of the stream at distance x_i. The summation is taken over all the values for a section. The hydraulic radius was then determined as $R = A/P$, where A is the cross-sectional area as shown in Figure 4. The stream depth was determined by dividing the area of the section by the width of the section. The slope of the stream was computed for each 500-foot section by dividing the change in the elevation of the surface of the stream by 500 feet. The hydraulic properties measured at each station are listed in Appendix AIII.

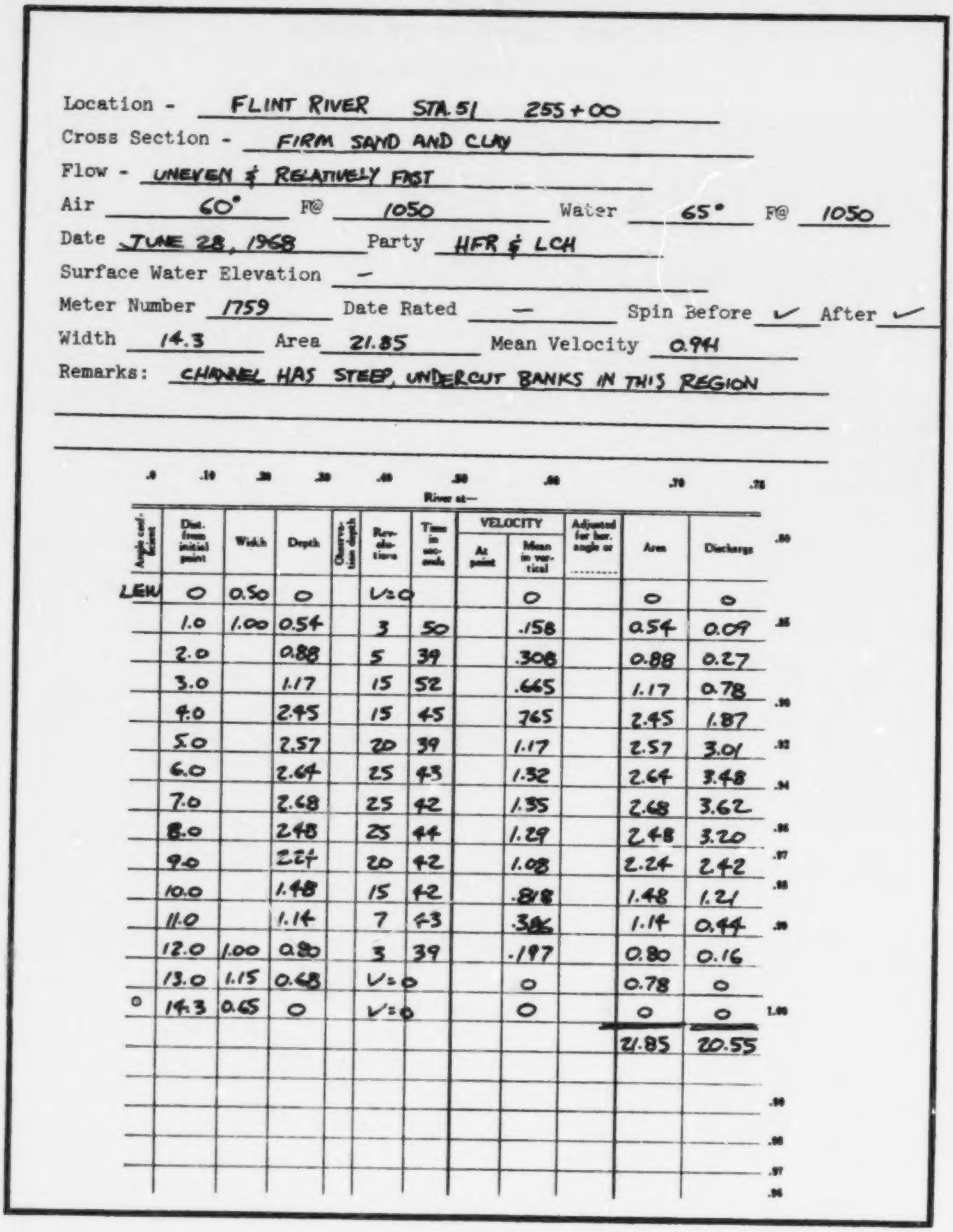
Additional discharge information was available from US Geological Survey gaging stations on the Flint and Chattahoochee rivers. Continuous water-level recordings at Georgia Highway 166 on the Chattahoochee and at Upper Riverdale Road on the Flint were utilized during the tracer studies. Measurements made by the Georgia Tech field team were used to establish the lower ends of the ratings. A typical rating curve is shown by Figure 5. Average discharge curves for the three streams are shown in Figures 6, 7 and 8.

Flow Adjustment. The stream discharge at the time of the tracer studies was usually somewhat higher or lower than the discharge at the time of the detailed hydraulic studies. Therefore it was necessary to adjust the measured hydraulic properties to the discharge conditions that existed at the time of the tracer studies. The adjustments were based on Manning's formula

$$Q = \frac{1.49}{n} A\ R^{2/3}\ S^{1/2} \qquad (36)$$

Figure 4

TYPICAL CROSS SECTION NOTES



Location - FLINT RIVER STA. 51 255+00

Cross Section - FIRM SAND AND CLAY

Flow - UNEVEN & RELATIVELY FAST

Air 60° F@ 1050 Water 65° F@ 1050

Date JUNE 28, 1968 Party HFR & LCH

Surface Water Elevation —

Meter Number 1759 Date Rated — Spin Before ✓ After ✓

Width 14.3 Area 21.85 Mean Velocity 0.941

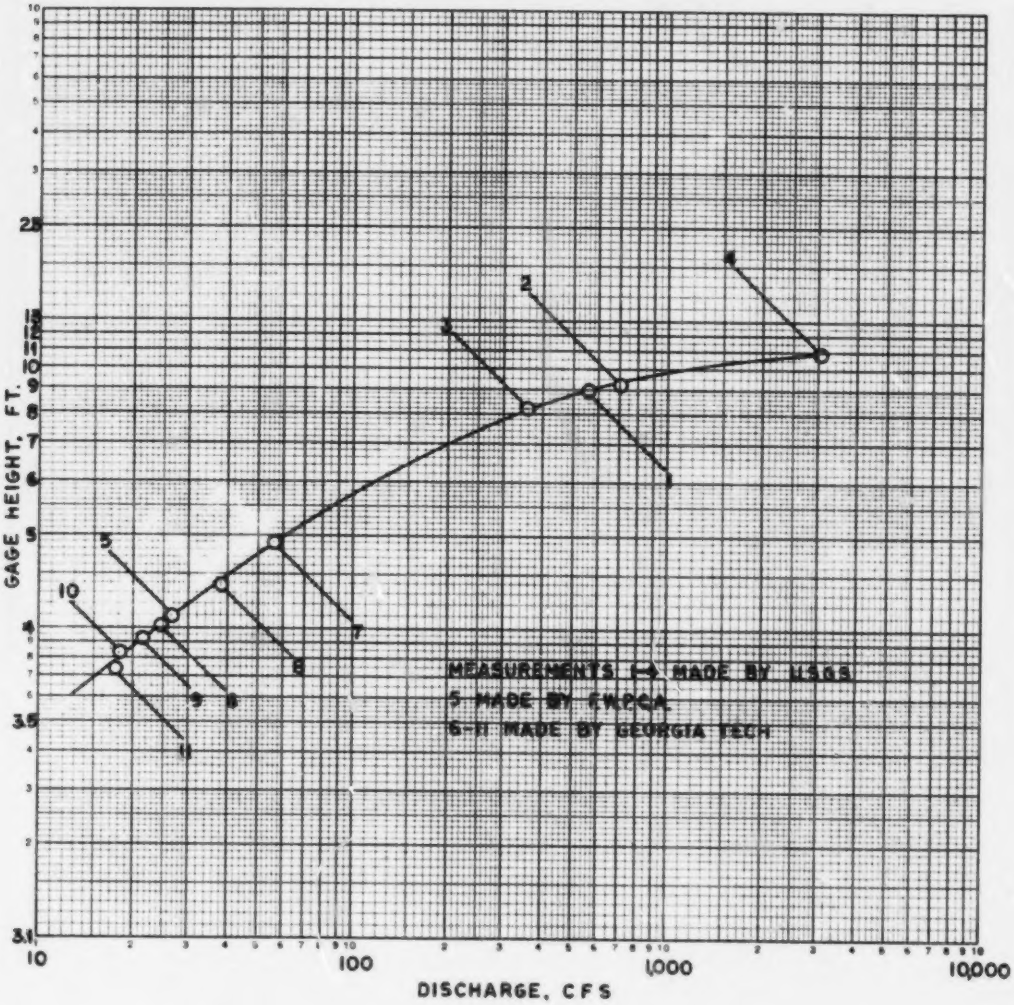
Remarks: CHANNEL HAS STEEP, UNDERCUT BANKS IN THIS REGION

River at—

Angle coefficient	Dist. from initial point	Width	Depth	Observation depth	Revolutions	Time in seconds	VELOCITY At point	VELOCITY Mean in vertical	Adjusted for hor. angle or	Area	Discharge
LEW	0	0.50	0		V=0			0		0	0
	1.0	1.00	0.54		3	50		.158		0.54	0.09
	2.0		0.88		5	39		.308		0.88	0.27
	3.0		1.17		15	52		.665		1.17	0.78
	4.0		2.45		15	45		.765		2.45	1.87
	5.0		2.57		20	39		1.17		2.57	3.01
	6.0		2.64		25	43		1.32		2.64	3.48
	7.0		2.68		25	42		1.35		2.68	3.62
	8.0		2.48		25	44		1.29		2.48	3.20
	9.0		2.24		20	42		1.08		2.24	2.42
	10.0		1.48		15	42		.818		1.48	1.21
	11.0		1.14		7	43		.386		1.14	0.44
	12.0	1.00	0.80		3	39		.197		0.80	0.16
	13.0	1.15	0.68		V=0			0		0.78	0
0	14.3	0.65	0		V=0			0		0	0
										21.85	20.55

FIGURE 5

RATING CURVE, FLINT RIVER AT UPPER RIVERDALE ROAD



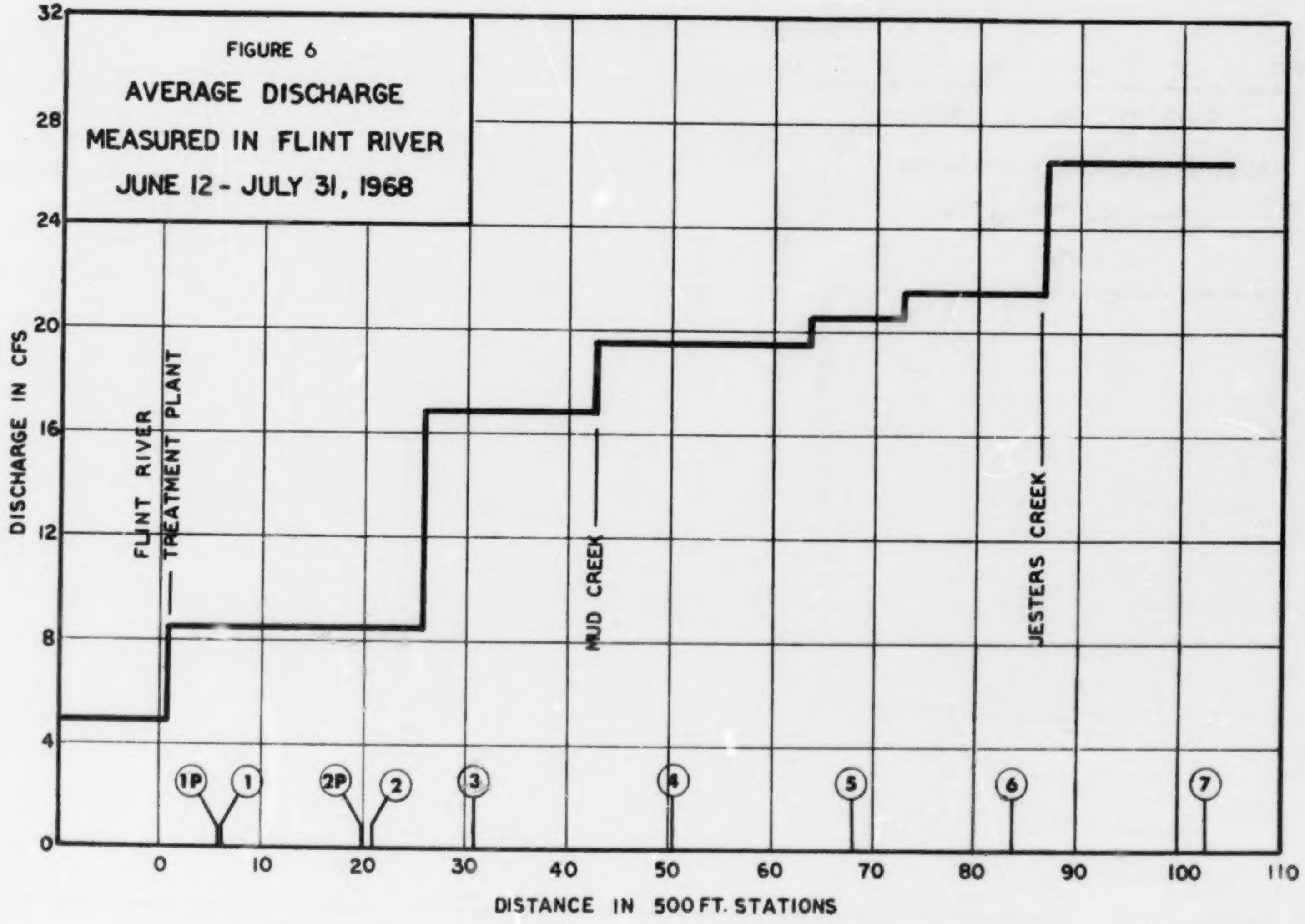


FIGURE 6

AVERAGE DISCHARGE
MEASURED IN FLINT RIVER
JUNE 12 - JULY 31, 1968

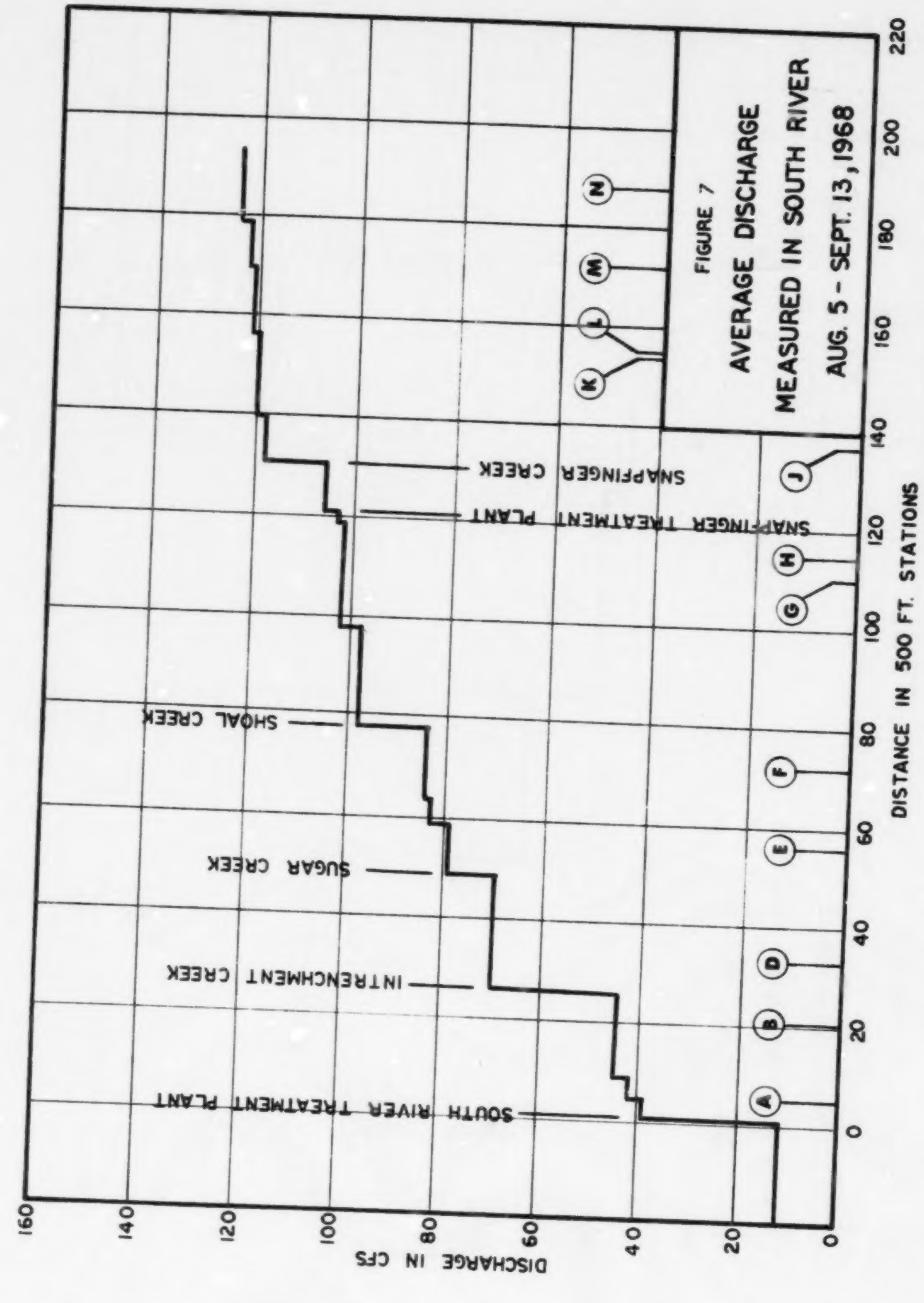


FIGURE 7
AVERAGE DISCHARGE
MEASURED IN SOUTH RIVER
AUG. 5 - SEPT. 13, 1968

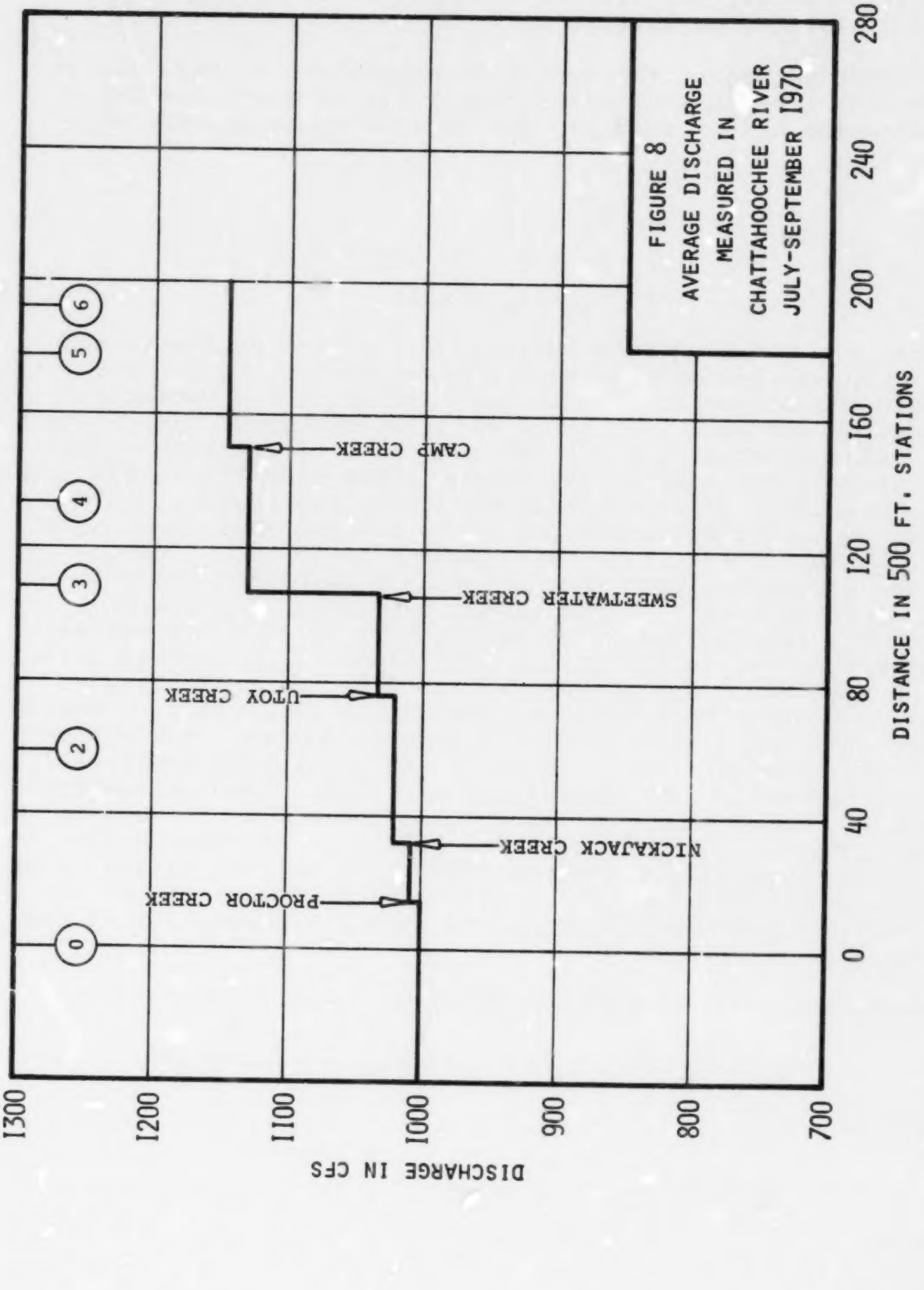


FIGURE 8
AVERAGE DISCHARGE
MEASURED IN
CHATTAHOOCHEE RIVER
JULY-SEPTEMBER 1970

in which Q = discharge (cfs); n = Manning's roughness coefficient; A = area of stream cross section (ft^2); R = hydraulic radius, A/P (ft); S = slope of the energy grade line; and P = wetted perimeter.

In order to adjust the hydraulic parameters at each of the 500-foot stations to values compatible with the discharge during the tracer studies, the following assumptions were made:

(a) $n_2 = n_1$
(b) $S_2 = S_1$
(c) $A_2 = A_1 + B_1\ \Delta y$
(d) $P_2 = P_1 + 2\ \Delta y$

where B = width of free surface, P = wetted perimeter and Δy = change in depth as flow changes from Q_1 to Q_2, and where the subscript 1 indicates the value of a variable measured during the original detailed survey of the rivers, and the subscript 2 indicates the value of a variable that existed at the time of the tracer study (see Figure 9). The discharge at each sampling station was measured at the time of the tracer study and hence the value of Q_2 at each of the 500-foot stations was readily estimated. Changes in n are negligible when the change in R is of the order of 0.1 foot or less[20]. The larger variations in R, i.e. $R_2 - R_1$, were of the order of 0.1 foot or less, therefore, assumption (a) is justified. The slope of the energy grade line may change appreciably if the river control changes. This can occur when a large increase in flow drowns a control such as a small fall or rock outcrop. However, the changes in discharge were small enough to rule out this occurrence. Thus, assumption (b) appears to be valid. Assumptions (c) and (d), taken together, imply that the sides of the streams are vertical. In general, this is a good assumption for the streams under study although it was not exactly satisfied at every cross section. The cross-hatched area on Figure 9 shows the area that is neglected when the assumption is not satisfied.

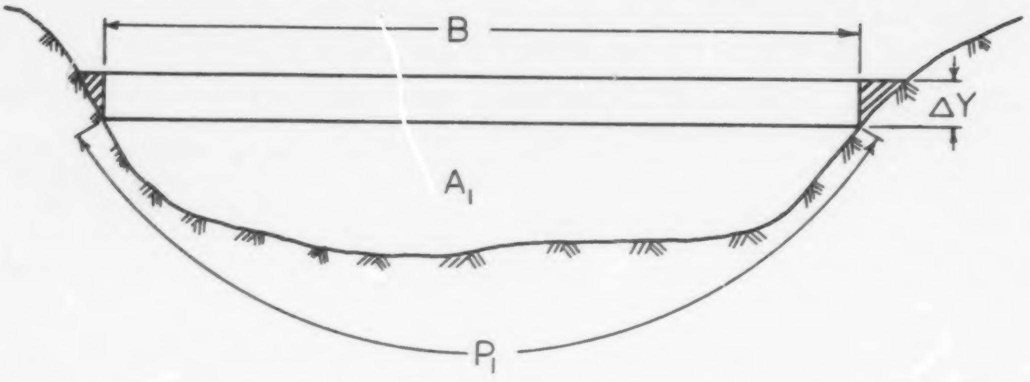
Assumptions (a) through (d) allow Q_2 to be written as

$$Q_2 = \frac{1.49}{n_1}\ (A_1 + B_1\ \Delta y)\left(\frac{A_1 + B_1\ \Delta y^{2/3}}{P_1 + 2\ \Delta y}\right) S_1^{\ 1/2} \qquad (37)$$

or

$$Q_2 = C_1\ (A_1 + B_1\ \Delta y)\left(\frac{A_1 + B_1\ \Delta y^{2/3}}{P_1 + 2\ \Delta y}\right) \qquad (38)$$

where



$$Q_1 = \frac{1.49}{n_1} A_1 R_1^{2/3} S_1^{1/2} \qquad (1)$$

$$A_2 = A_1 + B\Delta Y \qquad (2)$$

$$P_2 = P_1 + 2\Delta Y \qquad (3)$$

FIGURE 9

Flow Adjustment Procedure

$$C_1 = \frac{1.49\ S_1^{\ 1/2}}{n_1}$$

The constant C_1 can be computed from

$$C_1 = Q_1/A_1R_1^{\ 2/3}$$

and B_1 and P_1 are known. Therefore, for a known Q_2, equation (38) can be solved for Δy and A_2 and P_2 can be computed from assumptions (c) and (d). This was the procedure used in all adjustments of the measured hydraulic properties.

Figure 10 is a typical example of the tabulation of measured hydraulic properties as obtained directly from the field survey data. Figure 11 is the associated table of adjusted hydraulic properties for flows observed at the time of the reaeration tracer studies, and based upon the foregoing procedure for adjustment. Appendix AIII provides the detailed data for measured hydraulic properties for all of the stream sections studied.

Computed vs. Observed Velocities. Average values of the hydraulic properties were determined for each subreach, i.e., the reach of stream between each two sampling stations. The average value utilized for each geometric property, such as depth, area, etc., was the simple arithmatic mean. The average computed velocity for a reach was calculated from the relation

$$V = \frac{\sum L_i}{\sum L_i/V_i} \qquad (39)$$

where L_i is the distance between section i and section i + 1 and V_i is the arithmatic average of the measured velocity at section i and section i + 1. The velocities between sampling stations so determined were later compared with the velocities determined by the time required for the dye tracer to pass from one sampling station to another. The time of travel was defined as the peak-to-peak time from individual dye curves for each tracer release (see Figure 12).

A summary of the results of the velocity and traveltime comparisons is presented in Figure 13, which provides velocities obtained from the time-concentration curves from the tracer studies as well as those obtained by computation using equation (39). The velocity determined from the dye traveltimes did not always equal that determined from the detailed hydraulic measurements. In order to illustrate the difference in velocities obtained, the ratics of "measured"

Figure 10

Measured Hydraulic Properties For Flint River

Station 500 ft.	Velocity ft./sec.	Area ft.^{2}	Width ft.	Hyd. Rad. ft.	Wet. Per. ft.
0	1.14	4.33	6.60	0.58	7.51
1	0.64	19.76	14.30	1.15	17.24
2	1.00	7.70	13.00	0.56	13.68
3	1.25	9.41	12.60	0.70	13.51
4	0.48	17.46	15.50	1.03	17.02
5	0.23	36.33	34.00	1.01	35.87
6	0.21	41.99	27.60	1.38	30.45
7	0.12	71.13	45.60	1.49	47.89
8	0.34	24.91	21.50	1.10	22.74
9	0.61	12.30	17.20	0.69	17.86
10	0.65	11.21	18.80	0.58	19.46
11	0.80	10.32	19.20	0.51	20.08
12	0.57	19.79	17.20	0.50	39.62
13	0.90	8.23	16.40	0.47	17.55
14	1.13	6.60	10.60	0.60	10.93
15	1.14	5.99	16.50	0.35	16.97
16	0.98	6.44	19.60	0.32	19.85
17	1.27	6.51	16.00	0.40	16.17
18	0.89	9.52	14.60	0.64	14.84
19	1.09	6.63	16.50	0.38	17.33
20	0.56	13.85	21.00	0.63	22.13
21	0.18	45.26	23.60	1.75	25.87
22	0.34	32.50	20.20	1.47	22.10
23	0.55	18.61	10.70	1.38	13.50
24	0.55	13.53	14.10	0.86	15.78
25	0.95	7.45	13.40	0.53	14.16

Figure 11

Hydraulic Properties For Flint River

Adjusted To Average Discharge During Dye Studies

Station 500 ft.	Velocity ft./sec.	Area ft.^{2}	Δy ft.	Wet. Per. ft.	Hyd. Rad. ft.
0	1.32	5.78	0.22	7.95	0.73
1	0.52	14.04	-0.40	16.44	0.85
2	1.16	6.40	-0.10	13.48	0.47
3	1.03	6.89	-0.20	13.11	0.53
4	0.46	16.22	-0.08	16.86	0.96
5	0.22	33.61	-0.08	35.71	0.94
6	0.20	38.13	-0.14	30.17	1.26
7	0.11	65.63	-0.12	47.65	1.38
8	0.32	23.19	-0.08	22.58	1.03
9	0.60	11.96	-0.02	17.82	0.67
10	0.66	11.59	0.02	19.50	0.59
11	0.77	9.55	-0.04	20.00	0.48
12	0.48	15.32	-0.26	39.10	0.39
13	0.92	8.56	0.02	17.59	0.49
14	1.15	6.81	0.02	11.02	0.62
15	1.22	6.65	0.04	17.05	0.39
16	1.06	7.22	0.04	19.93	0.36
17	1.19	5.87	-0.04	16.09	0.36
18	0.84	8.64	-0.06	14.72	0.59
19	1.13	6.96	0.02	17.37	0.40
20	0.55	13.43	-0.02	22.09	0.61
21	0.18	41.96	-0.14	25.59	1.64
22	0.29	25.23	-0.36	21.38	1.18
23	0.49	14.97	-0.34	12.82	1.17
24	0.55	13.81	0.02	15.82	0.87
25	0.99	7.99	0.04	14.24	0.56

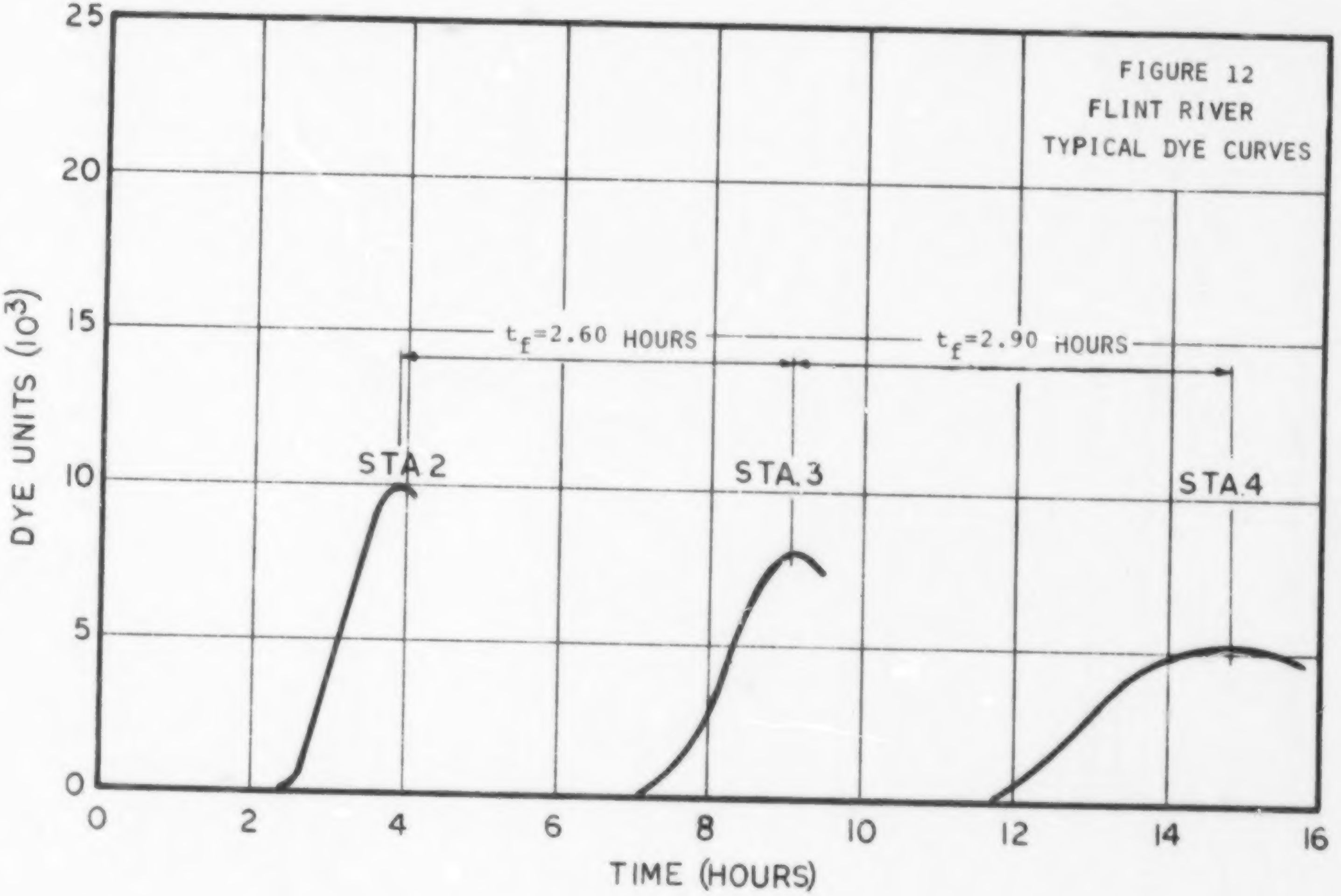


FIGURE 12
FLINT RIVER
TYPICAL DYE CURVES

Figure 13

Computed and Observed Velocities

Subreach	Computed Velocity (Fps)	Dye Velocity (Fps)	Ratio Computed/ Dye
FLINT RIVER			
Plant to Terrell Mill(01)	0.285	0.279	1.02
Terrell Mill to Lee's Mill(12)	0.500	0.474	1.05
Lee's Mill to Gravel Plant(23)	0.774	0.578	1.34
Gravel Plant to U. R'dale(34)	0.404	0.421	0.96
U. R'dale to Valley Hill(45)	0.595	0.477	1.25
Valley Hill to Wavelyn Way(56)	0.395	0.381	1.04
Wavelyn Way to End(67)	0.451	0.396*	1.14
SOUTH RIVER			
Plant to Bouldercrest(01)	1.41	1.40	1.01
Bouldercrest to P'ville(12)	1.26	1.13	1.12
P'ville to Waldrup(23)	1.48	1.48	1.00
Waldrup to Snapfinger(34)	1.20	1.21	0.99
Snapfinger to Panola(45)	0.78	0.86	0.91
Panola to End(56)	1.32	1.35*	0.98
CHATTAHOOCHEE RIVER			
0-2	1.64	1.71	0.96
2-3	1.58	1.76	0.90
3-4	1.75	1.85	0.95
4-5	1.57	1.72	0.92

*estimated value

Figure 14

SUMMARY OF HYDRAULIC MEASUREMENT PROCEDURES

PROPERTY	PROCEDURE
1. Reach Length	Taped along stream bank
2. Discharge	A. Current meter at each 500-ft. station during hydraulic studies B. Current meter at each sampling station during tracer studies; gage height at each rated section
3. Cross Section Area	A. Direct measurement at each 500-ft. station during hydraulic studies B. Direct measurement (for discharge) at each sampling station during tracer studies; area at each 500-ft. station adjusted to discharge at time of tracer release
4. Stream Depth	A. Computed from area divided by width of cross section for each 500-ft station. B. Average over subreach computed as mean of depths at each 500-ft station after adjustment for discharge at time of tracer release
5. Wetted Perimeter	From cross-section measurements for discharge determination. Adjusted for discharge for each tracer study
6. Slope	Difference in water surface elevation divided by length of reach, Δh/L. Δh was adjusted for discharge associated with each tracer

Figure 14 (continued)

SUMMARY OF HYDRAULIC MEASUREMENT PROCEDURES

PROPERTY	PROCEDURE
6. Slope (con't)	release
7. Hydraulic Radius	From cross-section measurements for discharge determination. Adjusted for discharge for each tracer study
8. Time of Travel	Peak-to-peak times from dye curves for each tracer release
9. Velocity	A. Discharge divided by area at each 500-ft station B. Average for subreach by equation (39) C. Average for subreach by dividing distance by dye time of travel

velocity to "dye" velocity were computed and are included in the tabulations. The average ratio for the South River was 1.01, the ratio for the Chattahoochee was 0.93 , while the average ratio for the Flint River was 1.16.

The higher value for the Flint River can be explained by referring to the general description of the streams. The channel of the Flint River is very irregular; it contains many small riffles and pools, and the channel is littered with debris. When the velocity was being measured with wading rod and current meter, the end of a 500-foot interval occasionally fell in a pool that was too deep to wade or often among debris such as tree tops that had been left from timber operations. The field crew therefore made the measurement slightly upstream or downstream at a better cross section. As a result, the velocities were higher, and the predicted time of travel less than those computed from the dye curves. The channel of the South is straighter, with fewer pools and more uniform depth (average ratio 1-01), and the channel of the Chattahoochee is the straighest and most uniform, with no real pools (average ratio 0.93).

Figure 14 summarizes the procedure used for the individual measurements made at each 500-foot section and the procedure used to determine an average value of each property over a subreach.

TRACER STUDIES

The field tracer studies of reaeration capacity were conducted generally in the same manner as those performed in the initial Jackson River field demonstration of the tracer technique[10], with minor modification. The analytical procedure for krypton-85 and tritium was also the same as the procedure developed earlier, in which the two radioactive tracers are counted simultaneously for the same sample by a liquid scintillation technique[10,21]. These procedures are described briefly here for purposes of completeness and continuity, and modifications are noted, and the reader is referred to the earlier publications for greater detail.

As indicated in Section IV of this report, the basic field procedure consists of releasing an instantaneous point dose of three tracers and subsequently observing the downstream concentrations at selected sampling points along the watercourse. The three tracers are rhodamine-WT fluorescent dye, tritium in the form of water molecules, and krypton-85 in the form of a fully dissolved gas. The three tracers are contained in a well mixed single dose, so that release of all three is truly simultaneous. The fluorescent dye is monitored continuously at each downstream sampling station by the use of a continuous-flow recording fluorometer, and thus provides accurate information as to time of flow. It also indicates when to sample for the other two tracers, which is accomplished primarily as the dye peak passes the specific sampling station. The tracer samples are subsequently analyzed in the laboratory for krypton-85 and tritium. The tritium provides an accurate measure of dispersion and dilution. The krypton-85, dispersed in identical degree due to the simultaneous dosing technique, provides the needed additional accurate information as to the gas transfer that took place between sampling stations. The theoretical basis of the analysis for gas transfer and reaeration capacity is provided in Section IV of this report, as well as in earlier publications[9,10].

Dose Release and Assay. In these more recent studies of the reaeration capacity of the Flint, South, Patuxent and Chattahoochee Rivers, the mixed doses of three tracers (dye, dissolved krypton-85 and tritiated water) were procured ready for immediate use from a vendor, in order to make best use of project staff time. (In the earlier Jackson River studies, the individual mixed tracer doses were prepared by project staff[10]). The required number of doses was delivered by the vendor by air and express to the Georgia Tech Radiation Safety Officer and stored for imminent field use. All of the doses were delivered in glass containers provided by Georgia Tech, so as to facilitate the field operation.

For the smaller streams (Flint, South, Patuxent) the individual mixed doses were of one quart size. This dose liquid volume was essentially all fluorescent dye (20 percent aqueous solution), with only a few ml of tritiated water and the dissolved krypton-85 added. Initial doses used in the Chattahoochee studies were about four liters in volume. However, these proved to be inadequate because of the great dilution and dispersion, and most of the latter Chattahoochee doses were about nine liters in volume, with proportionately larger quantities of the radioactive tracers (see Section VI).

The field tracer studies were conducted usually on Saturdays or Sundays or between school quarters, so as to avoid conflicts with the regular coursework of student project aides. This did not interfere with project objectives or scheduled progress, but in the case of the Chattahoochee studies it was observed that the BOD load from the Clayton STP in Atlanta was substantially lower on the weekends than during the usual work week.

Figure 15 illustrates the manual tracer dosing device used in the studies of the Flint, South and Patuxent Rivers. The base was a steel channel section (1" x 4") with smaller channels welded underneath it so as to keep the dose off the stream bed. The quart dose bottle was first taped to this base section. The top, or striker, section was a similar piece of steel channel with a four foot length of one-inch steel rod welded to it as shown. With the tracer dose bottle firmly taped to the base, the striker section was then also taped to the base, to complete the assembly for dosing (see Figure 15). To release the tracer dose, the assembly was carried by the vertical rod to the main channel of flow by wading, and placed firmly on a rocky section of the stream bed. The submerged dose could then be released by striking the top of the one-inch steel rod with a hammer, to shatter the glass bottle.

The dosing device shown in Figure 15 proved to be very dependable and satisfactory in all ways. Because of its simplicity, very little could go wrong with the dosing procedure. Its weight was sufficient to facilitate holding it steady, even in a strong current. Assembly of the dose was quick (three or four minutes), and this was of real assistance in minimizing any external radiation dose received by the personnel who conducted the dosing operation. The steel-to-glass contact resulted in thorough shattering of the glass bottle, and the actual tracer dose release was thus virtually instantaneous. After the release, still holding it by the vertical rod, the assembly could be readily washed and cleaned by rinsing it in the stream flow for a few minutes. Customarily, it was rinsed vigorously for a few minutes and then left submerged in the stream flow, to be retrieved some hours later after downstream sampling was complete.

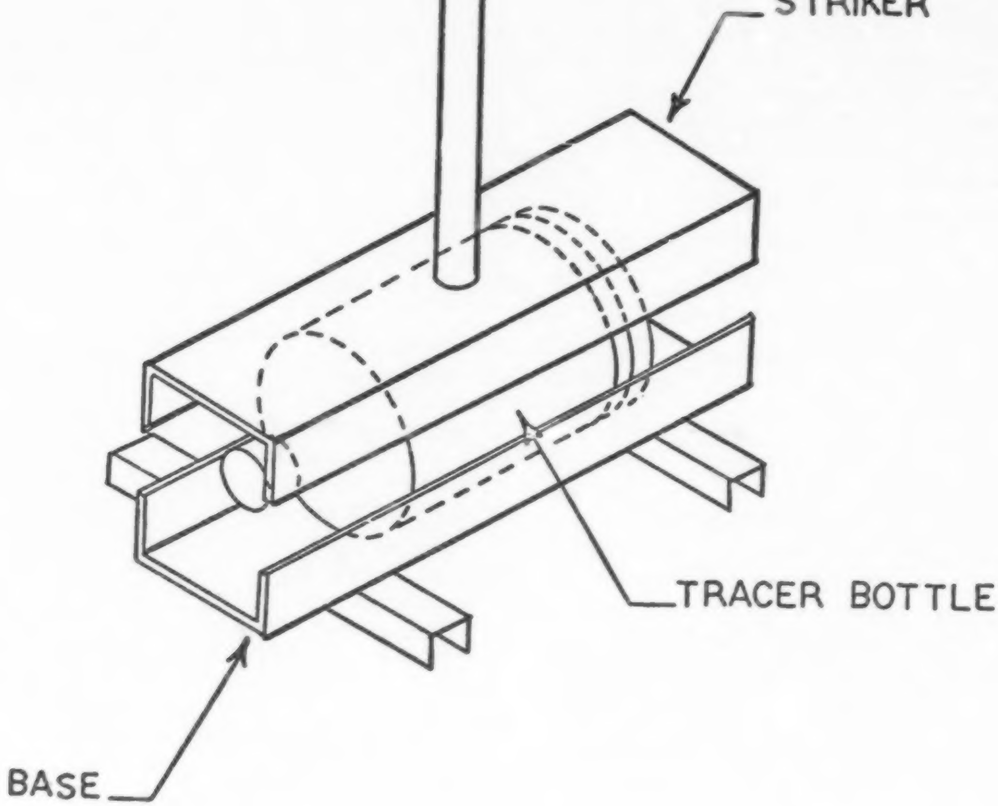
For the doses in the Chattahoochee River, which was much larger and too deep and swift to wade, the larger glass dose bottles were suspended, submerged and held in place by guy ropes from a bridge, and were then shattered by the use of blasting caps taped to the side of the bottle. This field procedure also proved fully satisfactory in terms of simplicity and minimum exposure of project personnel handling the dose bottle, and resulted in an instantaneous release for all practical purposes. These doses were submerged about two feet below the water surface and were rigged with a thin metal plate between the bottle and the water surface. Careful observation demonstrated that no splashing occurred on detonation of the caps.

The dose bottles were delivered with a rubber septum seal, so as to facilitate sampling by use of a hypodermic needle.

FIGURE 15

TRACER RELEASE DEVICE

(MANUAL)


STRIKER
TRACER BOTTLE
BASE

Initially, the smaller doses, and later the first of the larger Chattahoochee doses, were thus sampled directly for dose assay, by pressure pipette, before release. This procedure proved, however, to be somewhat undesirable in terms of preventing contamination of the external surfaces of the dose bottle. In the case of the larger doses, this procedure also required personnel exposure to the dose for longer periods of time (15 minutes or more) which, although quite safe by accepted standards, was nevertheless regarded as undesirable. Accordingly, a hand sampling procedure was devised to eliminate the need for direct dose assay. This was a miniaturized (to hold a one-ounce sampling bottle) DO sampler[12] attached to a long rod. The procedure consisted of sampling the dye patch a hundred yards or so below the dose point, before it became greatly dispersed. Several such samples could be obtained during passage of the dye patch, and it was found that they provided entirely satisfactory information as to the krypton:tritium ratio in the tracer dose.

It is worthy of mention that, no matter how much care is taken, glass bottles can be damaged in shipment, and this happened to one nine-liter Chattahoochee River dose during these studies. No damage or leakage was apparent until the drum shipping container was opened in the field for use. (Standard project procedure was to monitor the outside of the shipping container on receipt, and then leave it sealed until actual use in the field). At that time a cloud of gaseous krypton-85 was released and was detected by standard project safety monitoring procedures, which also were successful in preventing any unsafe exposure of project personnel. During subsequent safe disposal of that dose, it was ascertained that the bottle had been cracked in transit. This occurrence is noted here to emphasize the importance of following safe procedures in handling and using such materials.

Field Procedures. Field sampling procedures were essentially the same as those described earlier in connection with the Jackson River studies[9,10]. The field staff usually included about six undergraduate civil engineering student aides plus one or two faculty, the exact number depending upon the details of the specific study planned. One field sampling crew (three aides) set up the first downstream sampling station and began operation at about the time of dose release. Usually, time of flow to the first sampling station was several hours. After dose release, the dosing crew moved to the first sampling station to prove any assistance that might be necessary, then left once the first station was in satisfactory operation. A second field sampling crew moved in to set the second sampling station in operation several hours before tracer was anticipated at that location. On completion of sampling at the first station, that crew moved with its equipment to the third downstream sampling station, to set that in operation well before the appearance of dye. This leapfrogging was continued by the two field crews until the end of the study.

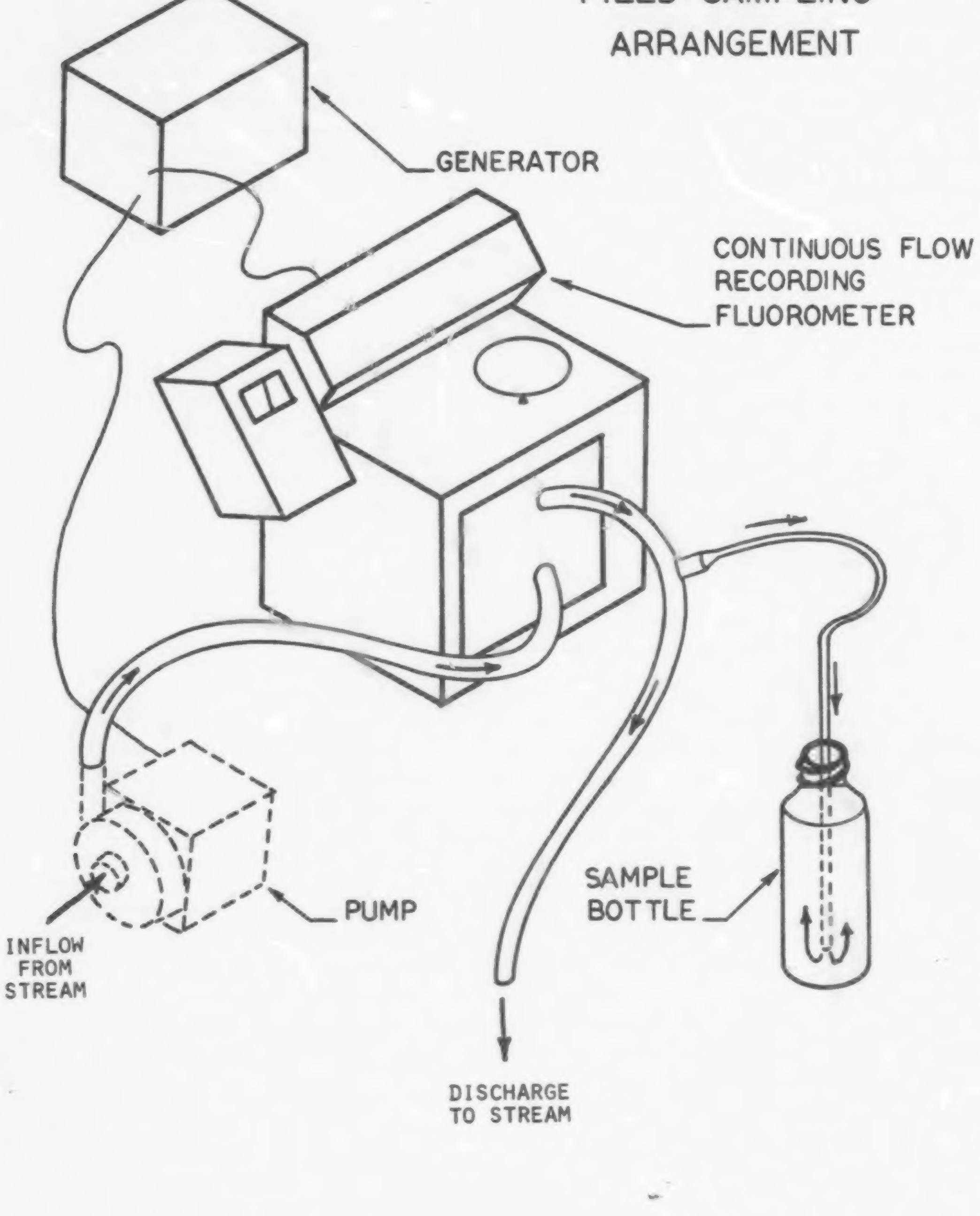
Two complete sets of field sampling equipment were thus kept in operation during each tracer study. A third complete set of equipment was kept available in the field vehicles as standby equipment.

The field sampling arrangement, and the associated equipment, was essentially the same as in earlier studies[10], and is shown schematically in Figure 16. The procedure consisted of placing a submersible pump in the main stream flow and pumping stream water to a continuous-flow recording fluorometer through a length of flexible hose. The pump and fluorometer were operated with power from a portable gasoline-powered generator located nearby. After passing through the fluorometer for measurement of dye concentration, the pump flow was split, with most being wasted back to the stream and a smaller flow being delivered to the bottom of a one-ounce glass sample bottle. The sample bottle was allowed to overflow until a sample was wanted, then removed slowly, capped with a pressure cap, numbered, and stored for transfer to the laboratory. A new sample bottle was then installed for the next sample. A background sample was taken at each station well before the arrival of any dye.

The fluorometer dial and recording chart were watched for arrival of the dye, and the chart was marked occasionally with the correct time and the corresponding dial reading. Sampling was begun soon after arrival of the leading edge of the dye mass, and continued with increasing frequency as the peak dye concentration approached. Each sample was numbered, and the sample number and time were marked in a field notebook as well as on the fluorometer recording chart. All samples were pressure-capped and sealed with black plastic tape. Sampling was usually discontinued after the dye concentration had dropped to about three quarters of the peak concentration.

The three streams (Flint, South, Chattahoochee) were all near Georgia Tech, where the liquid scintillation counter was housed, and the field samples were usually delivered to the counting laboratory within four or five hours after collection. The Project Chemist was on duty at the laboratory during the tracer studies, and the field samples were prepared for counting and set in the counter at once after receipt at the laboratory. At the worst, field samples waited

FIGURE I6
FIELD SAMPLING
ARRANGEMENT


GENERATOR
CONTINUOUS FLOW
RECORDING
FLUOROMETER
SAMPLE
BOTTLE
PUMP
INFLOW
FROM
STREAM
DISCHARGE
TO STREAM

no more than eight hours or so between collection and being placed in the laboratory counter.

Other field measurements were also made during the tracer studies, and other samples taken. River water temperature was observed and recorded several times at each sampling station, and water surface elevations observed relative to some fixed reference (e.g., a bridge). A separate crew gaged stream flow at key locations by standard procedures. DO and BOD samples were also taken, the former being evaluated by the azide modification of the Winkler Method.

Laboratory Procedures. The krypton-85 and tritium concentrations in the field samples were evaluated by a counting procedure developed earlier by Cohen et al[21]. In this procedure the two radioactive tracers are counted simultaneously in the same sample by liquid scintillation techniques, the counts being recorded separately by virtue of the difference in energy of the two different beta emissions. In brief, a 2-ml aqueous sample is mixed with about 20 ml of liquid scintillation solution (Butler's Solution) in a 25-ml glass counting vial, and the scintillations are counted for a fixed period (e.g., 20 minutes) in a liquid scintillation counter. The reader is referred to the earlier paper for greater detail[21].

Preparation of the individual field samples for counting consisted of transferring 2 ml from the one-ounce sample bottle to a counting vial about half full of Butler's Solution; the vial was then filled with additional Butler's Solution, capped, swirled to mix the water and counting solution, and set aside for subsequent counting. Three replicate vials were thus prepared for each field sample to be analyzed, and usually three samples (corresponding to peak dye concentration) were analyzed for each field sampling station. Thus, nine separate vials were counted for each sampling station. The liquid scintillation counter, in addition to automatic sample changing, also had provision for recycling samples, and the laboratory procedure included counting each vial at least twice. This procedure, involving considerable replication and long counting times, provided excellent counting statistics and accurate results for river samples having a count rate of as little as twice the background rate.

The procedure for transferring 2-ml portions of field sample to the counting vials is of special interest. Special precautions against loss of the dissolved krypton-85 are necessary - for example, the water cannot be poured out of the sample bottle, nor can it be subjected to the negative pressure associated with direct transfer by means of a hypodermic syringe. Figure 17 illustrates the procedure developed

PRESSURE PIPETTE

(NOT TO SCALE)

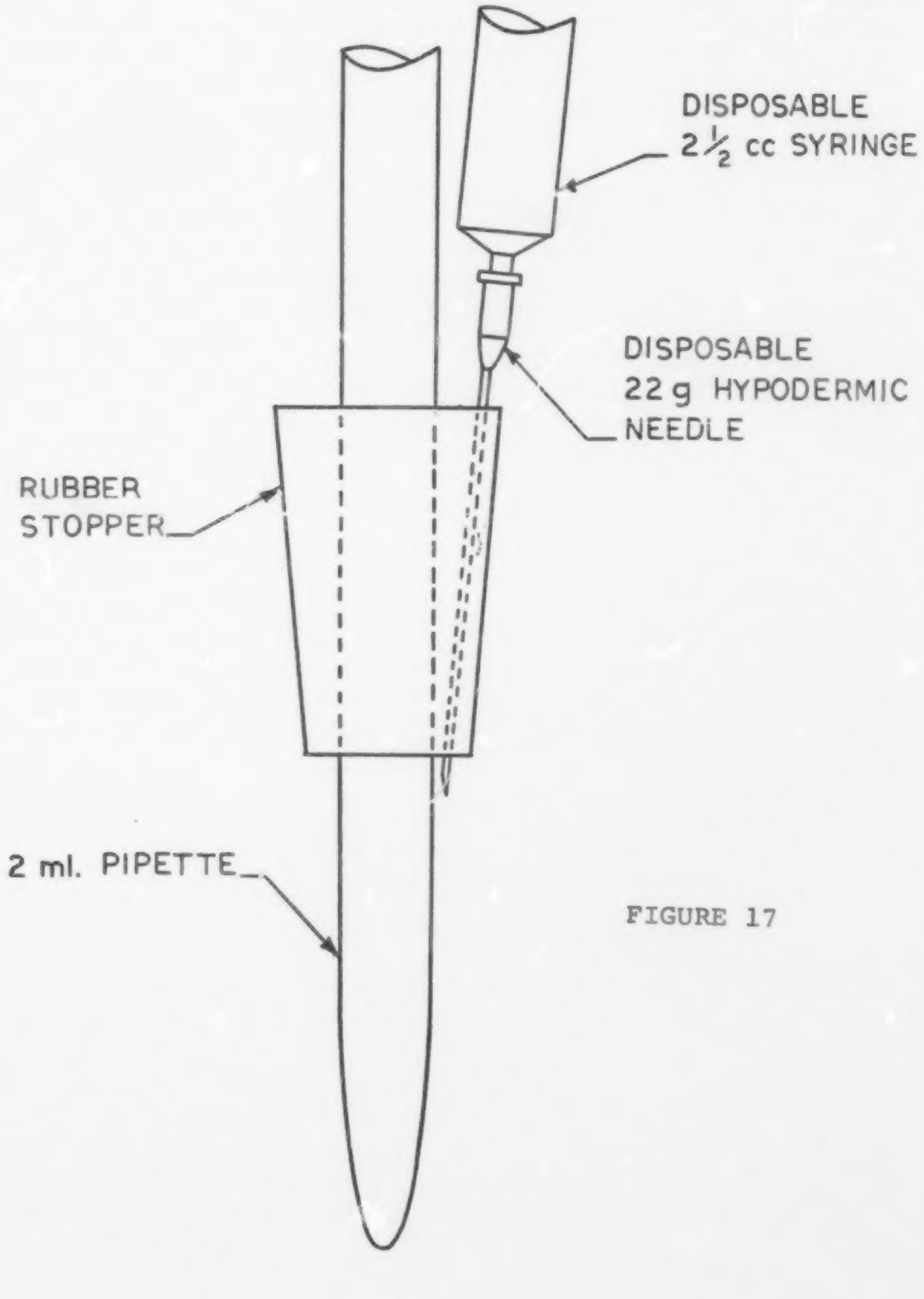

DISPOSABLE
2½ cc SYRINGE
DISPOSABLE
22 g HYPODERMIC
NEEDLE
RUBBER
STOPPER
2 ml. PIPETTE

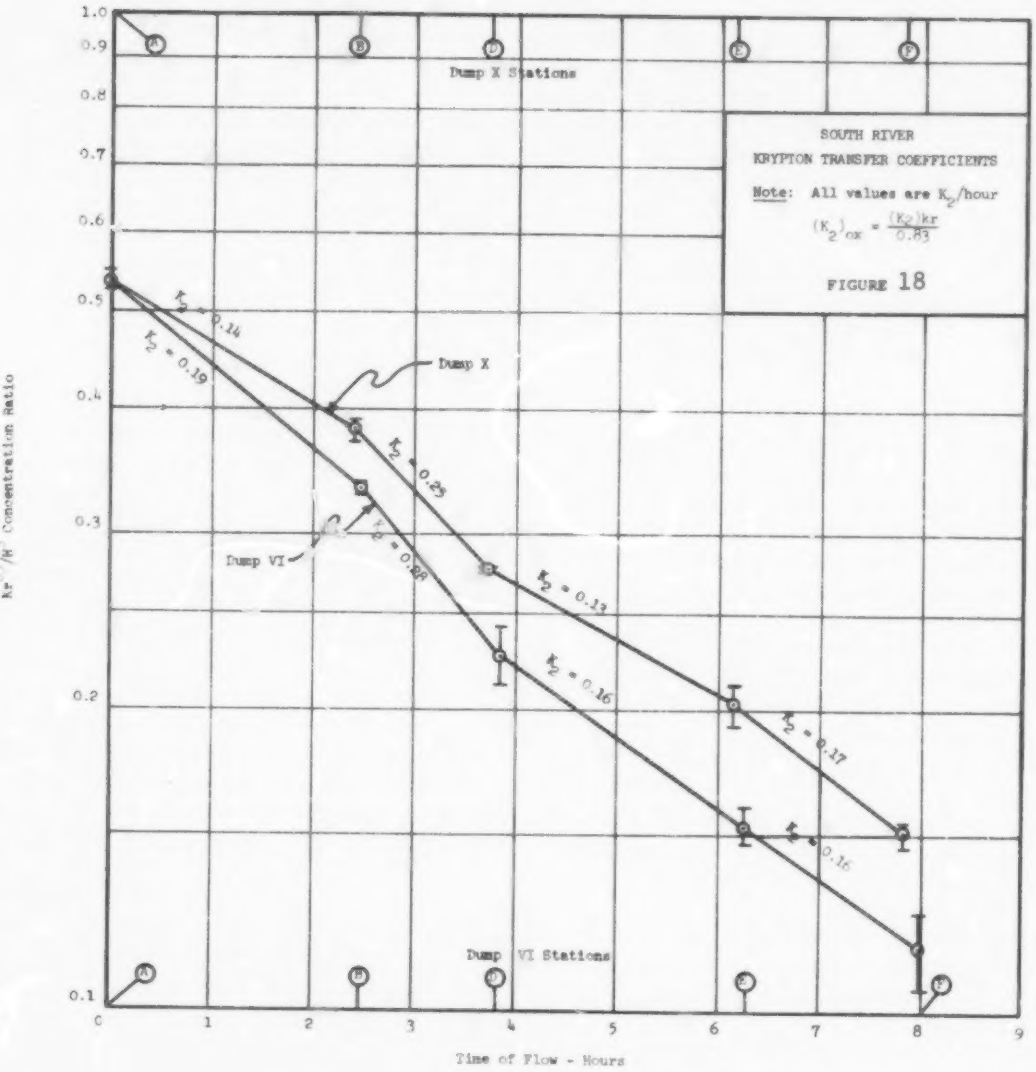
FIGURE 17

earlier[21], which involves pressure-pipetting. In brief, a rubber stopper that fits the sample bottle is prepared with a hypodermic needle and a 2-ml volumetric pipette, as shown. The needle tip projects barely through the stopper, whereas the pipette projects well into the sample water. The full sample bottle is opened and the prepared stopper firmly inserted. A fully opened syringe is then attached to the needle, and the plunger is pushed in slowly to force a measured amount of water up into the pipette. The stopper is then removed and the 2-ml portion transferred directly to the half-full counting vial, the water being allowed to run down the side of the bottle from a location just above the Butler's Solution. The aqueous sample falls directly to the bottom of the vial, under the counting solution, and thus has virtually no opportunity to lose krypton-85. This transfer procedure is repeated to fill the desired number of replicate counting vials. The vials are then filled to the top with additional counting solution, capped, and finally swirled to achieve a uniform mixture of sample and counting solution.

As noted above, usual practice was to prepare three replicate vials from each field sample for counting. In the case of the Chattahoochee River studies, where tracer concentrations proved to be especially low, five or six replicate counting vials were prepared for counting, to improve accuracy.

The liquid scintillation counter was calibrated against known standards to provide accurate counting efficiencies for tritium and krypton-85. Usual efficiencies in these studies were 25 to 28 percent for tritium and 86 to 90 percent for krypton-85. These efficiencies permitted accurate counting of river water samples having quite low tracer concentrations.

Figure 18 is a typical semilog plot of the results from one of the tracer studies, showing the usual way of plotting the krypton:tritium concentration ratios and the range of observation for each ratio. For each sampling station, the mean value for the three samples analyzed (total of nine vials) is shown by the small circle, and the range of results for the three samples (three vials each) is shown by the associated vertical line with brackets. Proceeding downstream in time, the tracer concentrations decrease, especially that of krypton-85, with corresponding increase in the range of observation of the ratio at each sampling station. In most cases, results were satisfactorily accurate at all stations, but in a few, where almost all of the tracer gas had been lost, the range of observation at the last downstream station was substantial. In such cases, the results presented



SOUTH RIVER
KRYPTON TRANSFER COEFFICIENTS

Note: All values are K_2/hour

$$(K_2)_{ox} = \frac{(K_2)kr}{0.83}$$

FIGURE 18

later (Section VI) are enclosed in parentheses to indicate uncertainty.

DO AND BOD STUDIES

During the studies of the reaeration capacity of the Flint, South and Chattahoochee Rivers, routine observation of DO and BOD was carried out as originally planned, according to standard analytical procedures[12]. To the extent possible, DO and BOD samples were taken at key sampling points at or near the time of passing of the dye peak associated with the gaseous tracer studies. DO's were analyzed in the field on collection, by the azide modification of the Winkler method, and river water temperatures were observed at that time. BOD samples were transported to the Georgia Tech laboratory and set up without delay. In a number of cases, the BOD analysis involved a BOD-time series, rather than only the 5-day observation.

As originally planned, this research incorporated limited oxygen balance studies in addition to the primary studies of the relationships between reaeration and hydraulic properties, for the sake of completeness and for the practical purpose of providing comprehensive information on real situations that involved serious pollution. For example, using the firm values of K_2 to be obtained from the gaseous tracer studies, it was hoped that highly accurate DO balances might permit improved evaluations of usually neglected natural processes such as benthal decomposition and respiration by attached oxidizing growths. Unfortunately, in streams as polluted as the Flint and South proved to be, the performance of complete and accurate oxygen balance analyses can be a major project in itself, and such detailed evaluations of other natural processes proved for the most part to be complex beyond the practical limitations of available staff and funds.

Relevant observations of DO and BOD are presented in the following report section on Experimental Results, together with appropriate discussion.

POLLUTANT EFFECTS ON REAERATION

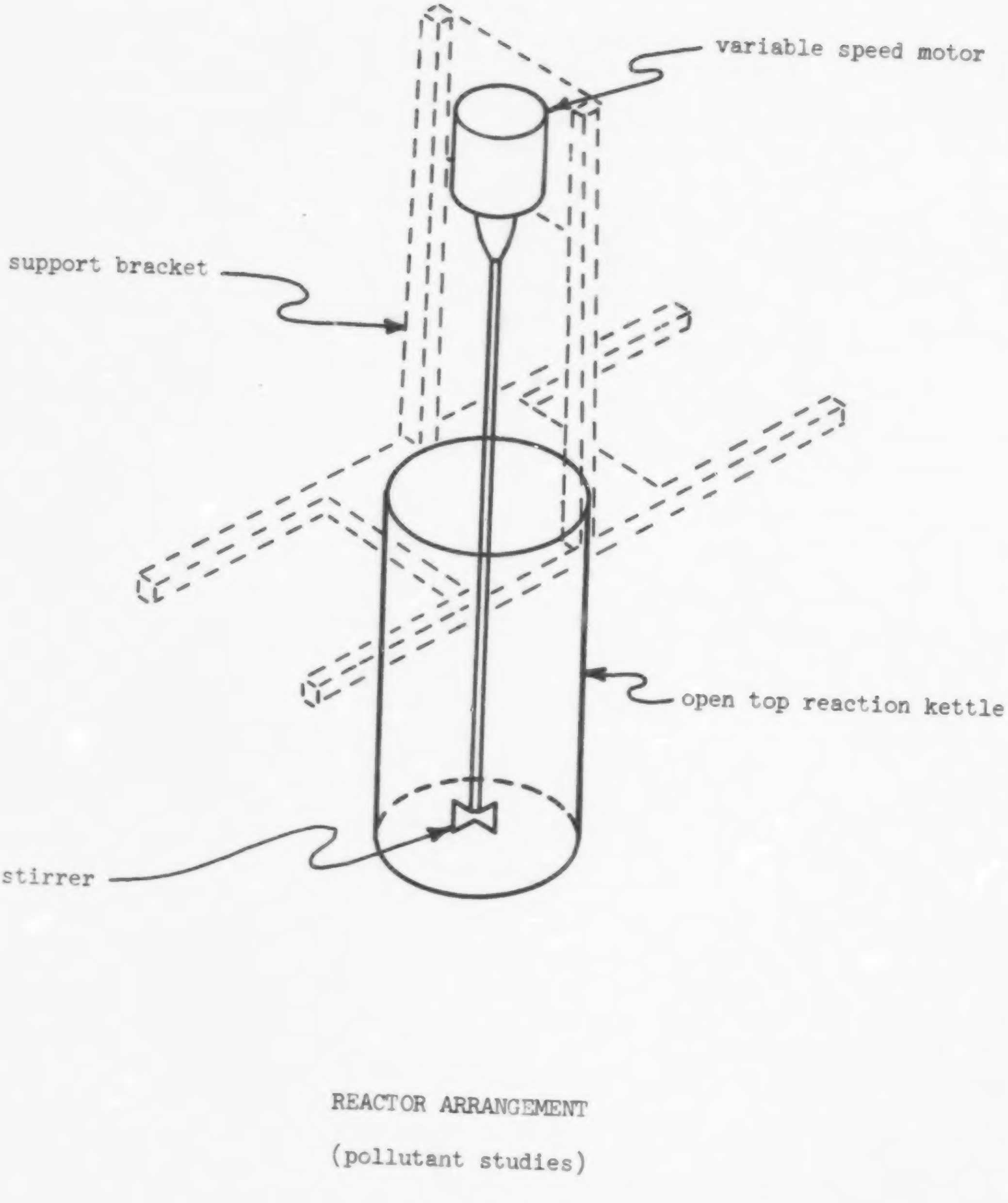
Various pollutants alter the ability of gas molecules to enter and escape water. This alteration causes the value of K_2 to vary under identical hydraulic and environmental conditions, depending upon whether clean water or polluted water is flowing in the stream. The pollutant effect on reaeration is not only related to the pollutant constituents and concentrations but also the turbulent mixing regime within the fluid. In order to evaluate the effect of various pollutants on reaeration, a series of laboratory tests was conducted on both natural and artificial stream waters.

The Pollutant Effect Reactor. A constant temperature, open top reactor, as shown in Figure 19 was constructed for the purpose of comparing the reaeration rates of various test waters under the same hydrodynamic and environmental conditions. The test reactor consisted of a support bracket to which an open top glass reaction kettle was mounted. A variable speed stirrer provided the mixing action. The stirrer motor was rigidly attached to the support bracket so that the reaction kettle and stirrer maintained their respective positions relative to each other. Constant temperature water was circulated around the reaction kettle for the purpose of temperature control.

The reactor system was all glass, with the exception of the stainless steel impeller and shaft. The reactor could be operated with a maximum water volume of 4 liters.

Operation of the Pollutant Effect Reactor. In the typical test the reactor was initially dismantled, thoroughly cleaned, and rinsed with distilled water a minimum of five times before reassembly. A predetermined volume of distilled water (3,600 ml) was then added to the reactor and allowed to stir until thermal equilibrium was attained. The stirrer was stopped and a single homogeneous tracer dose of tritiated water and dissolved krypton-85 was added below the test water surface, in 2 ml of distilled water contained in a pipette. The stirrer was started again and not stopped until the end of a run. Radiotracer samples were taken from the reactor by means of immersion of a 2-ml pipette until test water filled the pipette to a point above the fiducial mark. The pipette was then withdrawn from the reactor and a 2-ml sample was transferred to a liquid scintillation counting vial that had been previously filled with 10 to 15 ml of Butler's solution containing the liquid scintillator. After the transfer was complete, the vial was then filled full with Butler's solution, capped, and loaded into the liquid scintillation counter. The time at which each sample was taken was recorded in the notes.

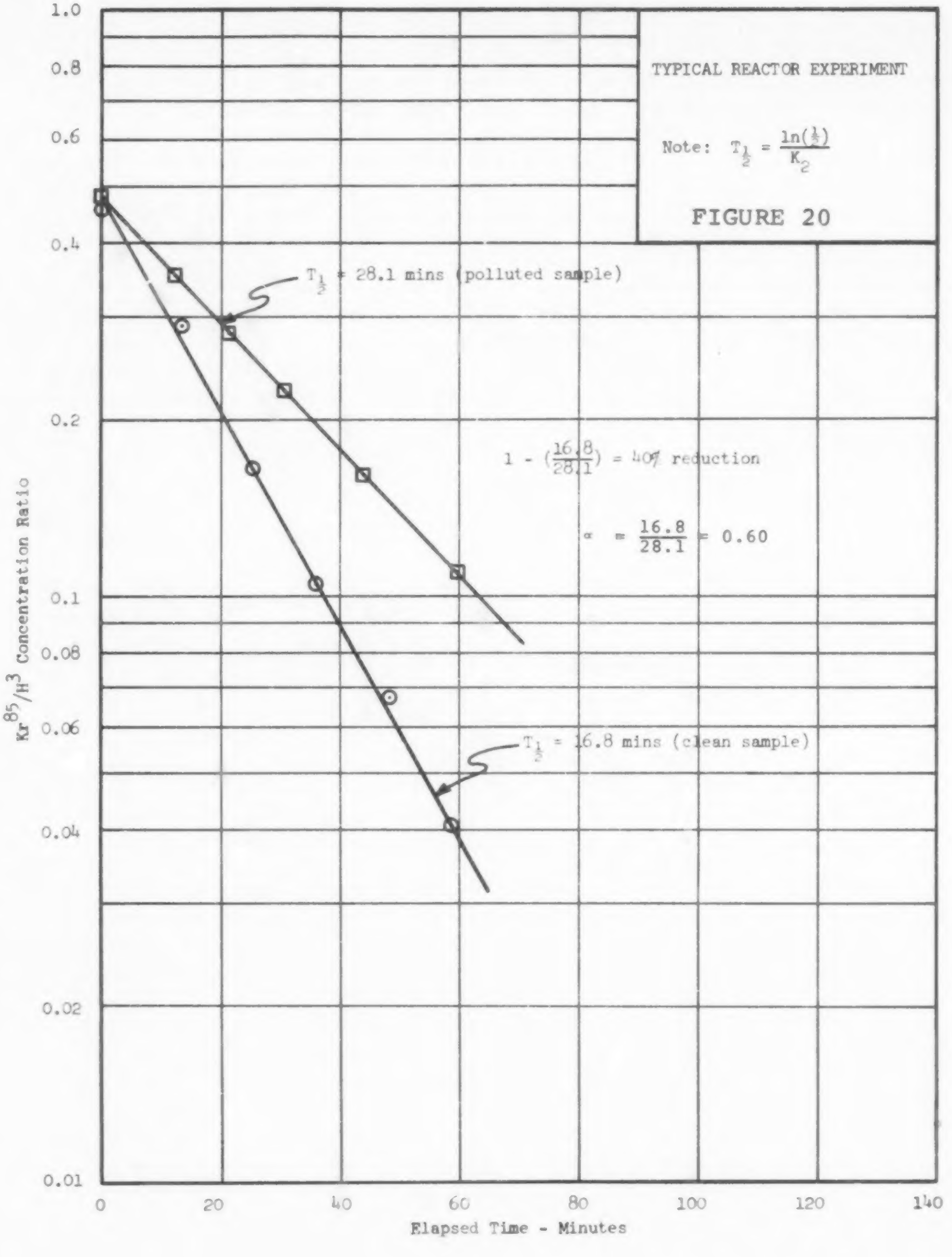
After the completion of a distilled water test, the reactor was drained by means of a siphon and thoroughly rinsed without dismantling or moving the system. A predetermined volume (equal to the volume of distilled water used in the preceding test) of polluted water was then added to the system and the test was conducted again as described above. Several times during each test, the speed of the stirrer shaft was determined and recorded in the notes.


variable speed motor
support bracket
open top reaction kettle
stirrer

REACTOR ARRANGEMENT

(pollutant studies)

FIGURE 19



TYPICAL REACTOR EXPERIMENT

Note: $T_{\frac{1}{2}} = \frac{\ln(\frac{1}{2})}{K_2}$

FIGURE 20

Computation of the Pollutant Effect. For each reactor run, the krypton:tritium concentration ratios associated with each sample analyzed were plotted as a logarithmic function of time. The line of "best fit" was then obtained by the method of least squares fitting of the linearized data. The slope of this best fit line was then recorded as the K_{kr} for the particular run. By comparing the K_{kr} for each pair of reactor runs (distilled and polluted) the pollutant effect could be determined. Figure 20 shows a typical pair of laboratory test results for the detergent surfactant LAS (linear alkyl sulfonate) in distilled water. The K_{kr} associated with the distilled water run was 0.0412 /min. while the K_{kr} associated with the LAS polluted water test was 0.0246/min. The pollutant effect on reaeration during this particular test reduced the gas transfer rate coefficient by 40 percent. Much of the available literature describes the pollutant effect on the reaeration rate coefficient as

$$\alpha = \frac{K_2\text{, polluted}}{K_2\text{, clean}} \qquad (40)$$

The alpha value will be less than unity if gas transfer is reduced by the pollutant, greater than unity if gas transfer is enhanced by the pollutant, and unity if the pollutant has no effect on gas transfer. The alpha value for the test shown in Figure 20 is therefore

$$\alpha = \frac{16.8}{28.1} = 0.60$$

In order to assure the same hydrodynamic conditions in a typical series of tests with a specific pollutant, the tests were conducted in fixed sequence such that each test with a specific pollutant concentration was conducted between two distilled water tests. During the test series the stirrer speed and position, volume of test water, temperature, etc., were never changed. The observed values of K_{kr} in the distilled water tests thus provided the necessary basis for verifying hydrodynamic uniformity throughout the test series, each test with polluted water being bracketted by a pair of distilled water tests having essentially the same K_{kr}.

SETTLEABILITY OF TRITIATED WATER

Early in the project it was suggested by individuals outside Georgia that tritiated water molecules, being heavier than ordinary water molecules, might tend to settle instead of remaining uniformly dispersed in river waters during the field tracer tests. Even though such a suggestion represents a clear denial of basic laws of physics and chemistry, it was felt that the simplest and clearest response would be experimental, and the following experiment was therefore conducted. (It is worthy of mention also that the nuclear power industry has for some years been seeking a practical process for for separating tritiated water from its wastes, and would hardly have missed the above possibility if it had any faint semblance of validity.)

Figure 21 shows the experimental column designed and fabricated for this study. The column was of glass, 36.5 inches in height and 2.75 inches in diameter. Four sampling ports were built in at heights as shown, and closed by use of a rubber serum cap, so that a hypodermic needle could be inserted through the serum cap directly into the center of the column and a 2.0 ml sample withdrawn.

The experimental column was housed in a small storage room used only by project personnel (completely unused during the period of study). This room was air-conditioned, with thermostatically controlled temperature. The column was rigidly supported with clamps to a rigid steel post, which rested on the concrete floor in the basement of a building. This arrangement minimized any possible vibration.

The experimental procedure was as follows: the column was filled with water containing some tritiated molecules. A total volume of 3400 ml was used. A small amount of food coloring was added also. The contents were stirred magnetically until the food coloring appeared uniform throughout. The stirrer was then stopped. A set of samples was taken at once (about 2.5 ml from each port) as indicated above, with careful attention to avoiding any agitation of the liquid in the column. The set of four samples was then immediately set up for counting and 2.0 ml portions were counted in the liquid scintillation counter. Additional sets were taken in the same manner at intervals through a period of 120 hours, as shown below:

Depth, inches below water surface	Observed Tritium Count Rate, cpm/ 2 ml at t=0 hrs	at t=1.6 hrs	at t=19.3 hrs
4.1	11,675	11,747	11,588
14.1	11,818	11,958	11,740
24.1	11,918	11,635	11,765
33.9	11,762	11,968	11,750

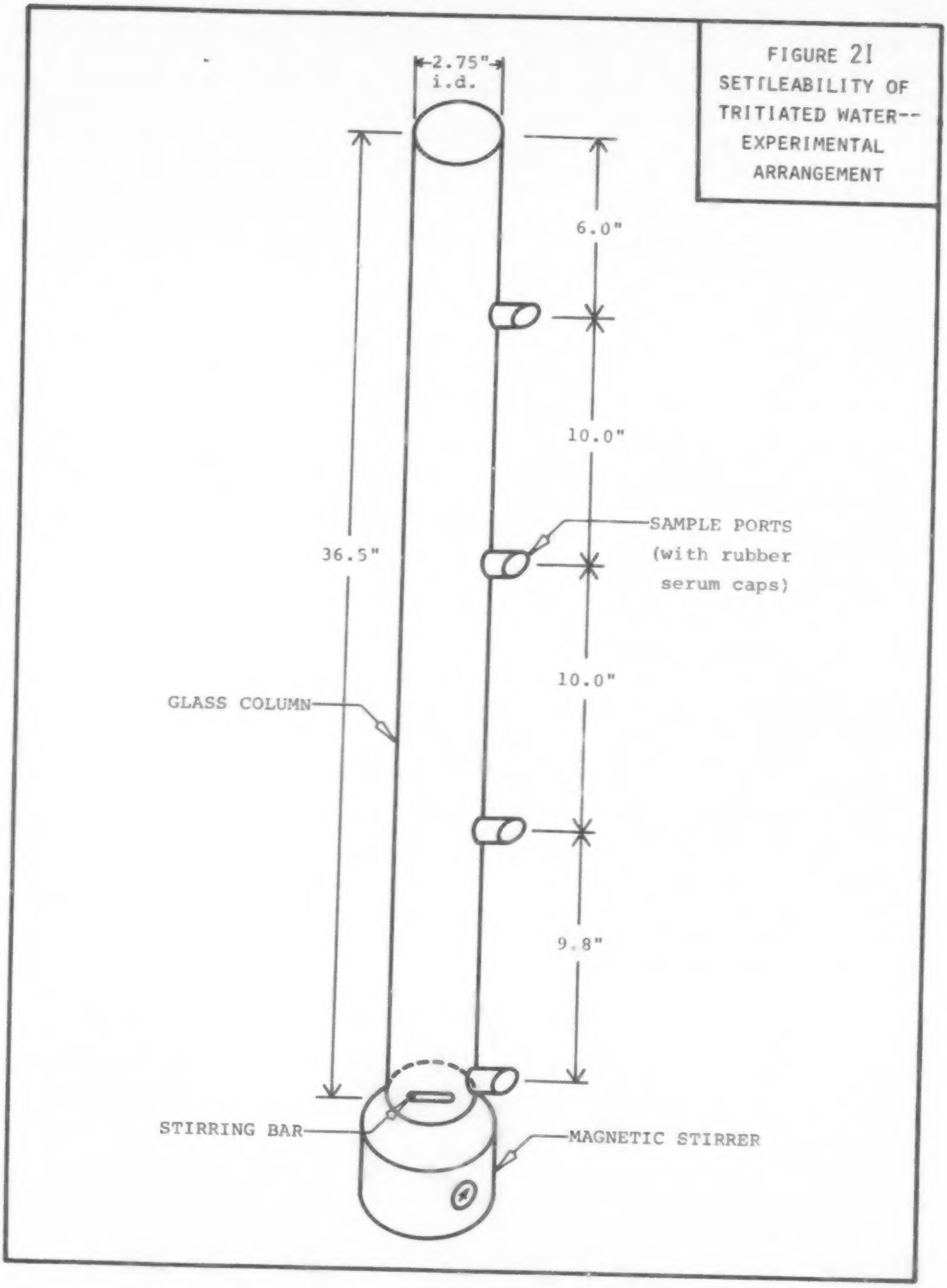


FIGURE 21
SETTLEABILITY OF
TRITIATED WATER--
EXPERIMENTAL
ARRANGEMENT

2.75"
i.d.
6.0"
10.0"
SAMPLE PORTS
(with rubber
serum caps)
36.5"
10.0"
GLASS COLUMN
9.8"
STIRRING BAR
MAGNETIC STIRRER

(continued)

Depth, inches below water surface	Observed Tritium Count Rate, cpm/2 ml at t=73.1 hrs	at t=118.8 hrs
4.1	11,547	11,658
14.1	11,602	11,755
24.1	11,522	11,793
33.9	11,527	11,688

The above demonstrate clearly that no settling of the tritiated water molecules occurred over the period of study. The very small differences in count rate that occurred were the result of usual counting statistical deviations and the small errors involved in the volumetric transfers (two percent or less). These differences were quite random, as expected, and there was no statistically significant variation of count rate with depth for any of the sets of samples.

In contrast to this experiment, in which every reasonable effort was made to maintain a quiescent volume of water, the field tracer experiments are conducted in water that is turbulent. They are completed in a matter of 10 to 20 hours, rather than several days. It is clear, from these considerations and the foregoing data, that settling of tritiated water molecules in the field tracer studies does not occur to any significant degree.

These results were, of course, as expected.

SOURCES OF ERROR

Although every effort was made during the studies reported here to eliminate and minimize experimental error, it is inevitable that some error or discrepancy will occur in any research, especially when field operations are involved. The kinds of error usually involved in stream physical studies, and their likely degrees, are commonly understood and need not be discussed in detail here--reference to Figure 14 should suffice to call them to mind. However, certain other kinds of deviation or error are not so obvious at first glance. Some of these became evident especially during the analysis and interpretation of the field results, and it was only then that they could be adequately defined in terms of their degree of importance. Such errors are discussed below.

Counting Statistics. In all of the field tracer studies performed it was attempted to obtain maximum information with the minimum dose of radioactive tracers. Doses were minimized for reasons both of cost and personnel safety. Obtaining maximum information often meant that the sampling was extended too far downstream from the dose point, so that at the farthest downstream stations very little tracer gas remained in the river water. In such cases, the krypton-85 count available from the liquid scintillation counter was too small, compared to the background count, for statistical accuracy. Usually this was obvious, and the data for the sampling station were accordingly rejected. However, in a few cases the statistical accuracy (the variance) appeared acceptable even though the counts were low, and the data were retained. Occasionally, subsequent analysis of the field results showed such data to be unacceptable after all, for reasons of such low count rates. Such cases are identified in Section VIII of this report, and involve data specifically from two South River releases.

Dose Assay. As indicated earlier the smaller (one quart) tracer doses used in the Flint, South and Patuxent River studies were sampled directly by pressure pipette before release, so as to provide an assay of the dose itself. This procedure not only provided verification of the quantities of tracer received from the vendor, but also provided the necessary krypton: tritium concentration ratio for the dose point in the river. About midway in these studies the hand sampling procedure was also initiated during the Patuxent River studies, as analysis of prior results occasionally gave some cause to suspect the direct dose assay by pressure pipette. In brief, the results of all of the studies indicate that although most of the direct dose assays were good, an occasional one yielded a false krypton: tritium concentration ratio. Subsequent analysis and interpretation led to the conclusion that in such cases the krypton-85 and tritium were most probably not uniform in concentration in the dye within the dose bottle--the triple tracer dose was probably not wholly uniform in the bottle, even though subsequent handling and deliberate mixing in the field before release resulted in a satisfactorily uniform released dose. A specific example of this discrepancy is identified in Section VIII of this report in connection with dose number VIII in the South River.

Nonuniform Mixing. As indicated in Section IV of this report and discussed in greater detail in Sections VI and VIII, most theoretical analyses of the relationships between gas transfer on the one hand and turbulent mixing or hydraulic properties on the other require the assumption of uniform or homogeneous turbulent mixing. In contrast, the field tracer method for gas transfer measures the gas transfer that actually occurs, whether mixing in the stream is uniform or not. Hence, in stream reaches where turbulent mixing is not uniform, some discrepancy between observed gas transfer and that predicted from theory must be expected. For the most part in the studies reported here the assumption of uniform mixing appears to be quite acceptable. However, in the case of one reach in particular, namely, the long, deep pool above Panola Shoals in the South River, mixing is clearly not uniform or homogeneous. In that case, the inflowing water clearly does not usually mix uniformly with the pool contents, and this leads to more than usual variability in gas transfer. This matter is described in greater detail in Sections VI and VIII of this report.

Pollutant Effect on Reaeration. As shown in the subsequent sections of this report, the presence of pollution can markedly modify the gas transfer capacity of water, both in the laboratory and in real streams. In stream situations where there is only a single major source of pollution, such as the Flint, Jackson, Patuxent and Chattahoochee River studies, the gas transfer capacity is modified according to the degree of pollution, but this does not create significant difficulty of interpretation in terms of the basic relationships between gas transfer and the stream hydraulic properties. However, where multiple major sources of pollution occur, as in the South River studies reported here, or where the pollution loads are highly variable from day to day, the resulting marked differences in pollutant effect from one reach to another, or from one day to another, can mask or confuse the analysis of gas transfer in terms of hydraulic properties. Such effects are described in detail in Section VIII of this report in connection with the South River studies.

Each of the above sources of discrepancy or error is readily recognizable and identifiable in the observed data if it occurs to any significant degree, and each of these kinds of discrepancy thus proved to be uncommon. Yet each also occurred at least once in recognizable degree and had to be reckoned with in the final analysis of results. These specific situations are clearly shown in the following sections of this report, especially in connection with the South River studies.

SECTION VI

EXPERIMENTAL RESULTS - FIELD STUDIES

This section of the report includes a summary of the relevant observed results from the field studies of the Flint, South and Chattahoochee Rivers, together with directly relevant discussion. Although not a part of this research project, the results of similar field tracer studies performed earlier on the Jackson River in West Virginia (1966) and on the Patuxent River in Maryland (1969) are directly applicable and are also included. The field survey results summarized here thus represent all such studies performed to date that have included both independent (tracer) observation of gas transfer capacity and detailed field measurement of the hydraulic properties. The detailed data from which these summarized results have been derived are included as Appendices to this report.

FLINT RIVER

The Flint River rises in the southwest region of the City of Atlanta and flows southward for approximately 350 miles before joining the Chattahoochee to form the Apalachicola, which then flows into the Gulf of Mexico. A headwater reach extending from the Flint River Sewage Treatment Plant (STP), located immediately south of the Atlanta Airport, to a location about 1.6 miles south of the intersection of the Flint River and Georgia Highway 138 was selected for study. The length of the river reach studied was 9.9 miles. Figure 22 is a general map of the Flint River study locale, and shows relevant features such as the Flint River STP, highways, tributary streams and river sampling stations.

The Flint River study reach includes a wide range of hydraulic features - the widest of any of the streams studied. The upper two miles are characterized by alternating riffles and small pools, and there are two larger mill ponds in this section of the river. These ponds are shallow, being almost filled with silt and sludge. At each mill pond site the flow spills over a dam and falls a distance of 10 to 12 feet. Below the second waterfall, the remainder of the study reach is characterized by a highly variable cross section, with a variable bottom of stone, clay or sand, and many sections of the stream contain old treetops resulting from timber operations along the banks. In addition, there are two sections, one about a mile in length and the other about 1.5 miles long, in which the stream flows in multiple channels. The meandering of the flow in these channels is difficult to

Preceding page blank

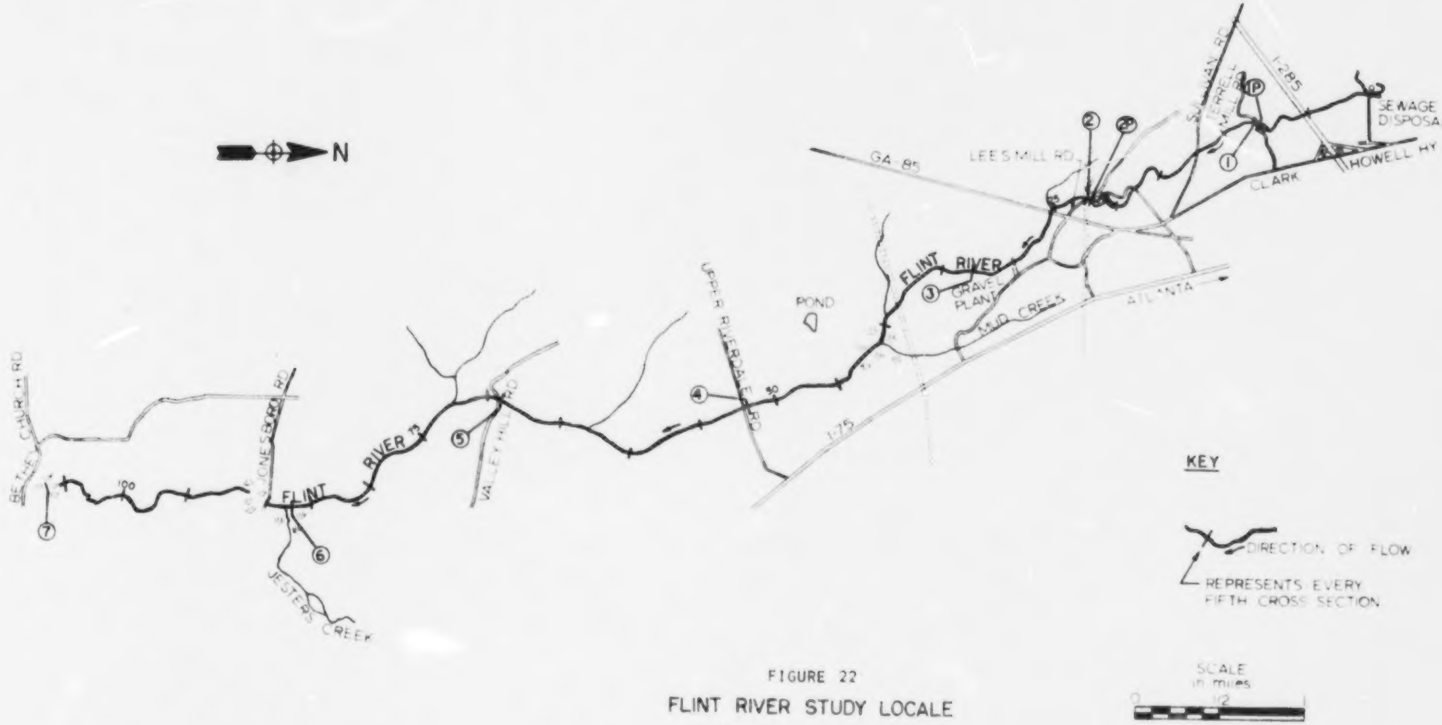

N
SEWAGE DISPOSAL
HOWELL HY
CLARK
I-285
SULLIVAN RD
TERRELL MILL RD
P
1
2
2a
LEE'S MILL RD
GA-85
FLINT RIVER
3
GRAVEL PLANT
MUD CREEK
ATLANTA
POND
UPPER RIVERDALE RD
4
50
I-75
VALLEY HILL RD
5
RIVER
75
FLINT
JONESBORO RD
6
JESTERS CREEK
100
BETHEL CHURCH RD
7
KEY
DIRECTION OF FLOW
REPRESENTS EVERY FIFTH CROSS SECTION
SCALE in miles
0
1/2
1

FIGURE 22
FLINT RIVER STUDY LOCALE
VICINITY OF ATLANTA

Table 1

Dosing Pattern, Flint River

Dump Number	Flint River Sampling Station Number 0	1P	1	2P	2	3	4	5	6	7
I	4/25 204 485									
II			5/2 182 463							
III	5/23 157 457									
IV						5/31 131 471				
V							6/13 419 420			
XII							8/25 190 650			
XIV	8/29 346 643									

Key: 5/2-Dump II released on 5/2/69-Station 1
182-182 mc of krypton-85 released
463-463 mc of tritium released

follow, and no single 'typical' cross section can be used to describe these stream reaches. One reach, about 0.3 miles long, is a marsh in which no meaningful velocity or cross-sectional measurements can be made.

Average discharge measurements made during the 1968 summer field hydraulic studies ranged from 5 cfs above the Flint River STP to 27 cfs at the lower end of the 9.9 mile study reach. Similar flows were encountered during the summer 1969 field tracer studies. The waste flow from the Flint River STP, at the upper end of the study reach, was the only significant source of pollution. At the time of these studies, the Flint River STP was a standard rate trickling filter plant with a design flow of 2.0 mgd, and was somewhat overloaded.

Dosing Pattern. Table 1 shows the dosing pattern that was used in the 1969 tracer studies of gas transfer in the Flint River. This pattern of seven separate releases was designed to provide a measure of gas transfer in each of the subreaches at least twice, as a test of reproducibility of results. As may be seen, the quantities of tracer were varied, the krypton-85 dose ranging from 131 mc to 419 mc and the tritium dose from 420 to 650 mc. A total of 1.63 curies of krypton-85 and 3.59 curies of tritium were released in the seven Flint River tracer studies, the average dose being 233 mc. of krypton-85 and 513 mc of tritium as tritiated water.

The study locale map, Figure 22, shows the locations of the sampling stations listed in Table 1, and Table AI.1; in Appendix AI, provides more detailed station descriptions. The stream sampling stations were located generally both for relationship to hydraulic features of interest and for accessibility.

Hydraulic Properties. The unusually wide variability of hydraulic features in the Flint River is clear from the descriptions of stations and reaches: referring to Figure 22, Station Number 0 was located about 200 feet downstream from the entry of the Flint River STP effluent, at a point where the effluent and the stream flow were apparently well mixed; proceeding downstream, the reach 0-1P includes a highly turbulent rapids section about 150 feet long emptying into the pond above the first waterfall - Dump XIV included additional sampling points immediately above and below the rapids sections; Station 1P was only a few feet above the dam; Station 1 was located about 100 feet below the first waterfall; the reach 1P-1 includes the first waterfall - the water falls about 10 feet onto granite surfaces, and the reach below the

Table 2

Typical Hydraulic Properties

Flint River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq.ft.	WS Elev Change ft	Bottom* Char
III	0-1P	10	2.72	3,000	0.31	1.19	33	9.9	Sand, mud
"	0-1	10	2.79	3,250	0.32	1.19	31	23.8	" "
"	0-2P	10	6.05	10,000	0.46	0.93	22	39.6	" "
"	0-2	10	6.47	10,500	0.45	0.93	22	51.7	" "
"	0-3	11	8.00	15,500	0.54	0.94	20	61.1	" "
III	1P-1	10	0.08	250	0.87	1.52	12	14.0	Rock
"	1P-2P	10	3.33	7,000	0.58	0.82	17	29.7	Sand, sludge
"	1P-2	10	3.75	7,500	0.55	0.82	18	41.8	" "
"	1P-3	11	5.28	12,500	0.66	0.88	17	51.2	" "
II	1-2P	10	3.12	6.750	0.60	0.82	15	15.8	Sand, sludge
"	1-2	10	3.47	7,250	0.58	0.82	16	27.8	" "
"	1-3	11	5.04	12,250	0.67	0.88	16	37.2	" "
"	1-4	16	10.24	22,350	0.61	1.34	26	57.8	" "
II	2P-2	10	0.35	500	0.40	1.83	24	12.0	Sand
"	2P-3	13	1.92	5,500	0.80	0.96	16	21.5	"
"	2P-4	19	7.12	15,600	0.61	1.61	31	42.0	Sand, sludge
II	2-3	14	1.57	5,000	0.88	0.96	15	9.4	Sand
"	2-4	19	6.77	15,100	0.62	1.61	31	29.9	Sand, Sludge
IV	3-4	22	4.95	9,600	0.54	1.95	40	20.5	Sand, Sludge
"	3-5	23	9.45	19,500	0.57	1.77	40	27.4	" "
"	3-6	24	14.77	27,600	0.52	1.70	47	36.1	" "

Table 2 (continued)

Typical Hydraulic Properties

Flint River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft	Bottom* Char
V	4-5	21	4.55	8,900	0.54	1.58	39	8.1	Sand, Sludge
"	4-6	24	9.90	17,000	0.48	1.57	49	16.8	" "
"	4-7	24	17.73	26,400	0.41	1.57	59		" "
V	5-6	25	5.35	8,100	0.42	1.55	58	8.9	Sand, Sludge
"	5-7	26	13.18	17,500	0.37	1.55	69		" "
V	6-7	28	7.83	9,400	0.33	1.56	84		Sand, Sludge

---

*Predominant bottom character

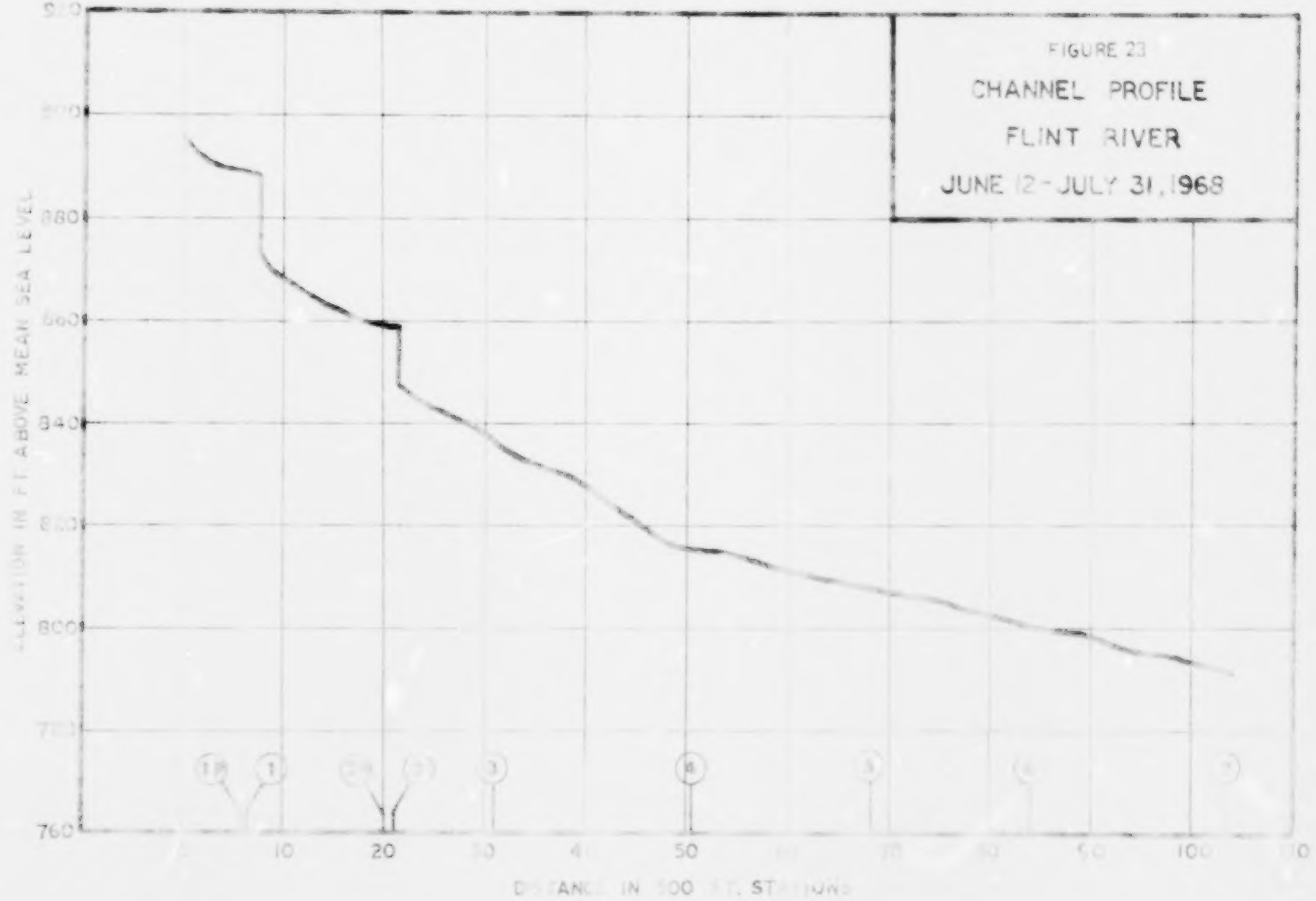


FIGURE 23

CHANNEL PROFILE

FLINT RIVER

JUNE 12 - JULY 31, 1968

fall remains quite shallow and fast above Station 1; the reach 1-2P is similar to the reach 0-1P, but contains no substantial rapids section; Station 2P was located at the downstream end of the second mill pond, a few feet above the dam; the reach 2P-2 includes the second waterfall (about 12 feet in height) and a relatively deep pool (6 to 8 feet deep) immediately underneath the fall, station 2 being about 100 feet downstream from the pool in the main channel; the reach 2-3 is characterized by alternating riffles and shallow pools, Station 3 being located just above a gravel plant; the marsh is located below Station 3, and Mud Creek enters the Flint at the lower end of the marsh - Dump IV included additional sampling stations above and below the marsh and in Mud Creek, and demonstrated that some water from the Flint River above the marsh (Station 3) crosses the marsh to enter Mud Creek and then returns to the Flint with the Mud Creek flow below the marsh; the remainder of the study reach, from Station 4 to Station 7, is relatively uniform, has a shallower slope, and becomes somewhat larger than the upstream section.

Figure 23 shows the Flint River channel profile for the reach studied. Table 2 summarizes the typical hydraulic properties of the sections studied. These results represent field measurements of relevant hydraulic features at 500-foot intervals, as described in greater detail in Section V. The detailed hydraulic properties are provided in Appendix AIII.

Reaeration Coefficients. Table 3 is a summary of all of the reaeration coefficients observed in the Flint River studies, for the main study reaches. These studies included seven separate tracer releases (Dumps I, II, III, IV, V, XII, XIV) as shown, and 56 separate main reach values of K_{OX} were observed. In most cases at least two separate values of K_{OX} were observed for the same reach, both in order to test reproducibility and to include different flow conditions when possible.

As indicated earlier, the Flint incorporates a very wide range of hydraulic features within the 10 miles or so studied, from waterfalls to rapids, pools and a swamp. As a result a very wide range of values of K_{OX} has been observed, from 0.099 to 15.1 per hour at 25°C. Referring to Table 3, the reach 1P-1 includes the first waterfall and the reach 2P-2 the second. The reach 0-1P includes a highly turbulent rapids section, and the reach 3-4 includes the swamp. These latter two reaches were the subject of special studies (Dumps IV and XIV), as noted below.

Reference to Table 3 indicates that in general the results

Table 3

Observed Reaeration Coefficients, Flint River Main Study Reaches

Reach	K_{ox} per hour @ 25°C							
	I	II	III	IV	V	XII	XIV	Mean
0-1P	-	-	0.166	-	-	-	0.143	0.155
0-1	0.314	-	0.450	-	-	-	0.377	0.380
0-2P	-	-	0.343	-	-	-	0.328	0.336
0-2	0.438	-	0.461	-	-	-	0.453	0.451
0-3	-	-	(0.420)	-	-	-	-	-
1P-1	-	-	10.2	-	-	-	15.1	12.7
1P-2P	-	-	0.488	-	-	-	0.541	0.515
1P-2	-	-	0.678	-	-	-	0.778	0.728
1P-3	-	-	(0.551)	-	-	-	-	-
1-2P	-	0.284	0.251	-	-	-	0.270	0.268
1-2	0.540	0.520	0.471	-	-	-	0.536	0.517
1-3	-	0.449	(0.403)	-	-	-	-	0.426
1-4	-	0.361	-	-	-	-	-	-
2P-2	-	2.72	2.22	-	-	-	2.89	2.61
2P-3	-	0.732	(0.663)	-	-	-	-	0.698
2P-4	-	0.397	-	-	-	-	-	-
2-3	-	0.280	(0.236)	-	-	-	-	0.258
2-4	-	0.271	-	-	-	-	-	-
3-4	-	0.268	-	0.236	-	-	-	0.252
3-5	-	-	-	0.185	-	-	-	-
3-6	-	-	-	(0.131)*	-	-	-	-
4-5	-	-	-	0.131	0.116	0.097	-	0.115
4-6	-	-	-	(0.080)*	0.107	0.100	-	0.104
4-7	-	-	-	-	0.112	0.111	-	0.112
5-6	-	-	-	(0.037)*	0.099	0.102	-	0.101
5-7	-	-	-	-	0.110	0.116	-	0.113
6-7	-	-	-	-	0.118	0.125	-	0.122

---

*Questionnable result - not included in mean.

are highly reproducible from one tracer release to the next, with few exceptions. The results that involve Station 6 in Dump IV are noted as questionnable because of very poor counting statistics (very little dissolved krypton-85 remained at Station 6 in that case). Certain other sources of deviation from the norm remain in the results--for example, Dump XIV took place at a considerably lower flow than occurred during Dumps I and III, and Dump XIV also took place on a Saturday at a lower than usual degree of pollution. The significance of these and other factors is discussed at a later point.

Reference to the data of Table 3 also indicates that, in terms of the gas transfer capacity, this section of the Flint can be conveniently regarded as three separate main reaches, namely, the reaches 0-2, 2-4, and 4-7. The reach 0-2 had a mean K_{ox} of 0.45 per hour at 25°C, within very narrow limits (0.44-0.46, three observations); the reach 2-4 is characterized by a K_{ox} of 0.26 per hour at 25°C, about half that of the reach 0-2, also within quite narrow limits (0.24-0.28, five observations over the reaches 2-3, 2-4 and 3-4); the lower study reach, 4-7, is characterized by a K_{ox} of 0.11 per hour at 25°C, also within very narrow limits (0.10-0.13, 13 individual reach observations).

It is evident also from these results that in a stream like the Flint much of the real work of gas transfer may take place in very short reaches. Thus, within the reach 0-2 most of the gas transfer occurred at the two waterfalls. This and other similar effects are more directly demonstrated by reference to Figures 24 through 26. Figures 24 through 26 are a graphical presentation of all of the gas transfer results for the Flint River. According to the theory, as outlined earlier, the observed krypton:tritium ratios have been plotted for each dump against time of flow on semilog scales, and the slope of the straight line between any two observed ratios represents the tracer gas transfer rate coefficient. (It should be recalled here that the logarithmic scale shown refers to common logs, and therefore to k_{kr}, whereas the numerical values shown on the graphs are referenced to the base e, and are values of K_{kr}). It should be noted also that in preparing these Figures it was desirable for purposes of clarity to displace certain stations in time--thus, for example, in Figure 24 (Upper Study Reaches) the results for Dump II are displaced to the right by about four hours, in order to avoid overlapping with Dumps III and XIV.

The numerical values of K_{kr} shown on the graphs are referenced to the prevailing river water temperatures at the time of the specific tracer release (see Appendix AIV for details).

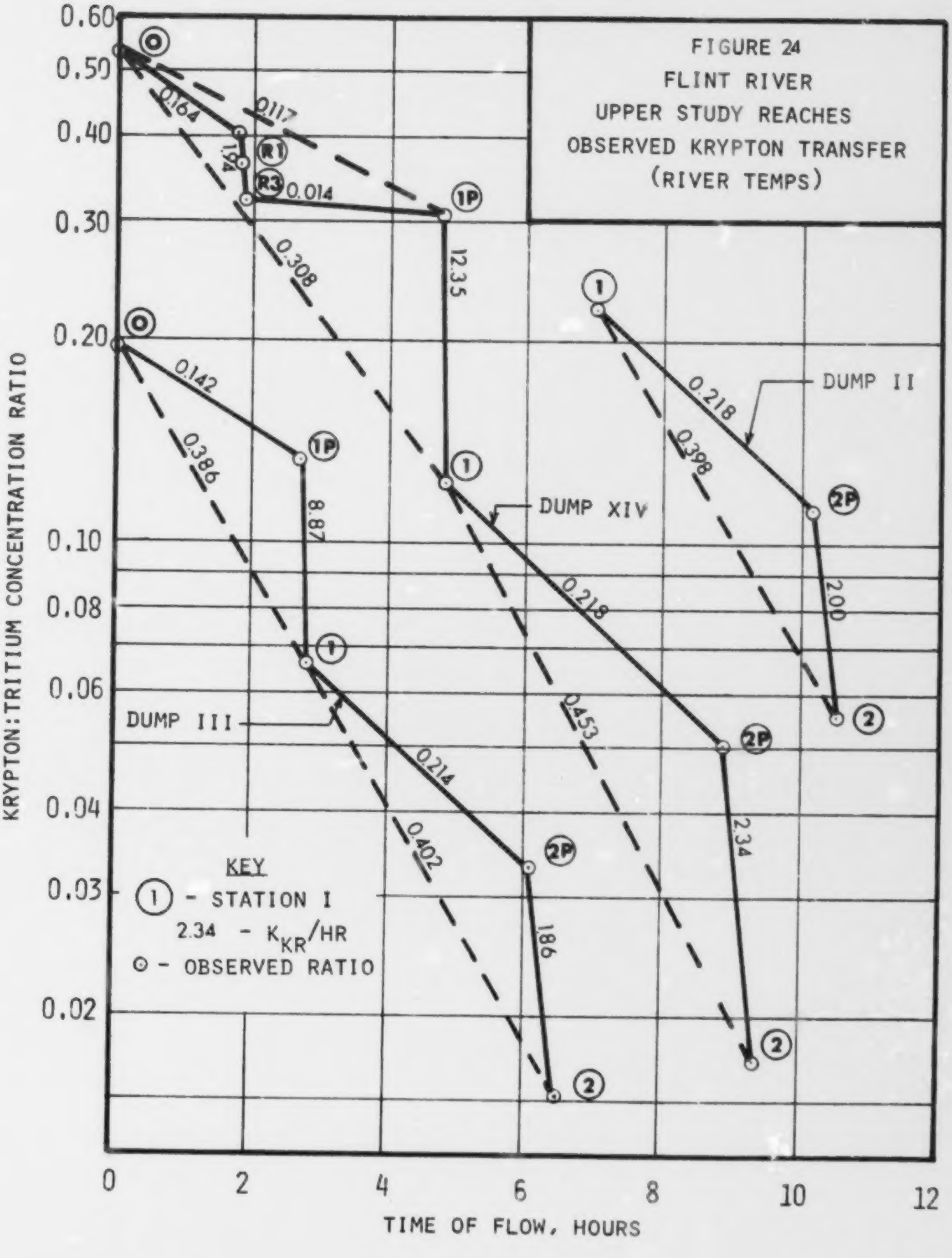


FIGURE 24
FLINT RIVER
UPPER STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS)

The values of K_{ox} at 25°C in the preceeding Table 3 have been obtained from these observed values of K_{kr} by use of the basic K_{kr}: K_{ox} ratio of 0.83 and the temperature correction coefficient $\theta = 1.022/°C$.

Referring now to Figure 24 (Upper Study Reaches), and noting the parallel nature of the lines, the reproducible pattern of gas transfer in the specific stream reaches is obvious. Dumps II and III were at comparable flows (about 10 cfs), whereas Dump XIV was at a lower flow (about 5 cfs). River temperatures were somewhat different (24-27°C for Dumps III and XIV, and about 19°C for Dump II). The observed values of K_{kr} ranged from a low of 0.014/hr (reach R3-1P, Dump XIV) in the pool above the first waterfall to 12.35/hr (reach 1P-1, Dump XIV) over the first waterfall.

Times of flow were considerably longer for Dump XIV, reflecting the lower flow, but this did not markedly affect the observed values of K_{kr} or K_{ox} at 25°C. The observed values of K_{kr} for specific reaches are highly consistent, allowing for the prevailing differences of river temperature, flow and degree of pollution.

Further and more direct comparisons can be made in terms of the actual loss of tracer gas in the specific stream reaches. Recalling that for any reach the decimal fraction of tracer gas remaining at the downstream station is just the downstream station krypton:tritium concentration ratio divided by the upstream station ratio, the fractions of tracer gas transfer for any specific reach may be compared for different dumps. For example, for the reach 1-2, Dump III, the observed krypton:tritium ratios were 0.0664 and 0.0152 at stations 1 and 2 respectively. Hence, at station 2 there remained 22.9 percent of the tracer gas that was present earlier at station 1:

$$\frac{0.0152}{0.0664} \times 100 = 22.9$$

In other terms, 77.1 percent (100-22.9) of the tracer gas was lost to the atmosphere between stations 1 and 2.

The reach 1-2 was included in all three dumps shown in Figure 24. The results of such computations show that for this reach the average tracer gas loss was 79.3 percent, with only slight variation:

Dump Number	Percent Tracer Gas Lost
II	74.9
III	77.1
XIV	85.9

Similar computations for the other upper study reaches demonstrate great consistency. For further example, for the reach 2P-2, which represents the second waterfall, an average of 57 percent of the tracer gas was lost, the observed range of results being 50-66 percent. All of the observed data have been reported in terms of percent loss of tracer gas, as well as in terms of K_{kr} and K_{ox}, and these results are presented also in Appendix AIV. This mode of interpretation of the data, and its significance, is discussed in greater detail in a subsequent Section of this report.

It is also evident from Figure 24 that for a stream like the Flint most of the gas transfer takes place in short reaches. This is obvious, so far as the two waterfalls are concerned, but is also seen to be true through the rapids section, R1-R3, contained within the reach 0-1P. Referring to Figure 24, it may be seen that the K_{kr} for the reach 0-1P has the values 0.117 and 0.142 per hour for Dumps XIV and III, respectively. However, the more detailed results obtained from Dump XIV show that, in fact, most of the actual gas transfer took place in the short rapids reach R1-R3, and that a very high K_{kr} prevailed there (1.94 per hour); in the pool R3-1P very little real gas transfer occurred, corresponding to a quite low K_{kr} (0.014 per hour). More specifically, in Dump XIV 42.6 percent of the tracer gas present at Station 0 was lost in the reach 0-1P, during the 4.74 hours time of flow; of this total gas loss, about 50 percent occurred in the reach 0-R1 (1.75 hours), 36 percent occurred in the rapids section R1-R3 (0.12 hours) and only 5 percent occurred in the pool section R3-1P (2.87 hours).

Figure 25 illustrates the observed data for the Middle Study Reaches, 2-4. Considering the reaches 2-3 and 3-4, the observed numerical values of K_{kr} are quite consistent (0.184-0.202 per hour). Dump IV included intermediate stations between 3 and 4, for purposes of further evaluating the effect of the swamp or marsh. As may be seen, the marsh itself, reach BS-AS, yielded a value of K_{kr} quite consistent with the other observed results, indicating that gas transfer through the marsh was not markedly reduced.

Figure 26 provides the observed results for the Lower Study Reaches, 4-7. The parallel lines again indicate highly

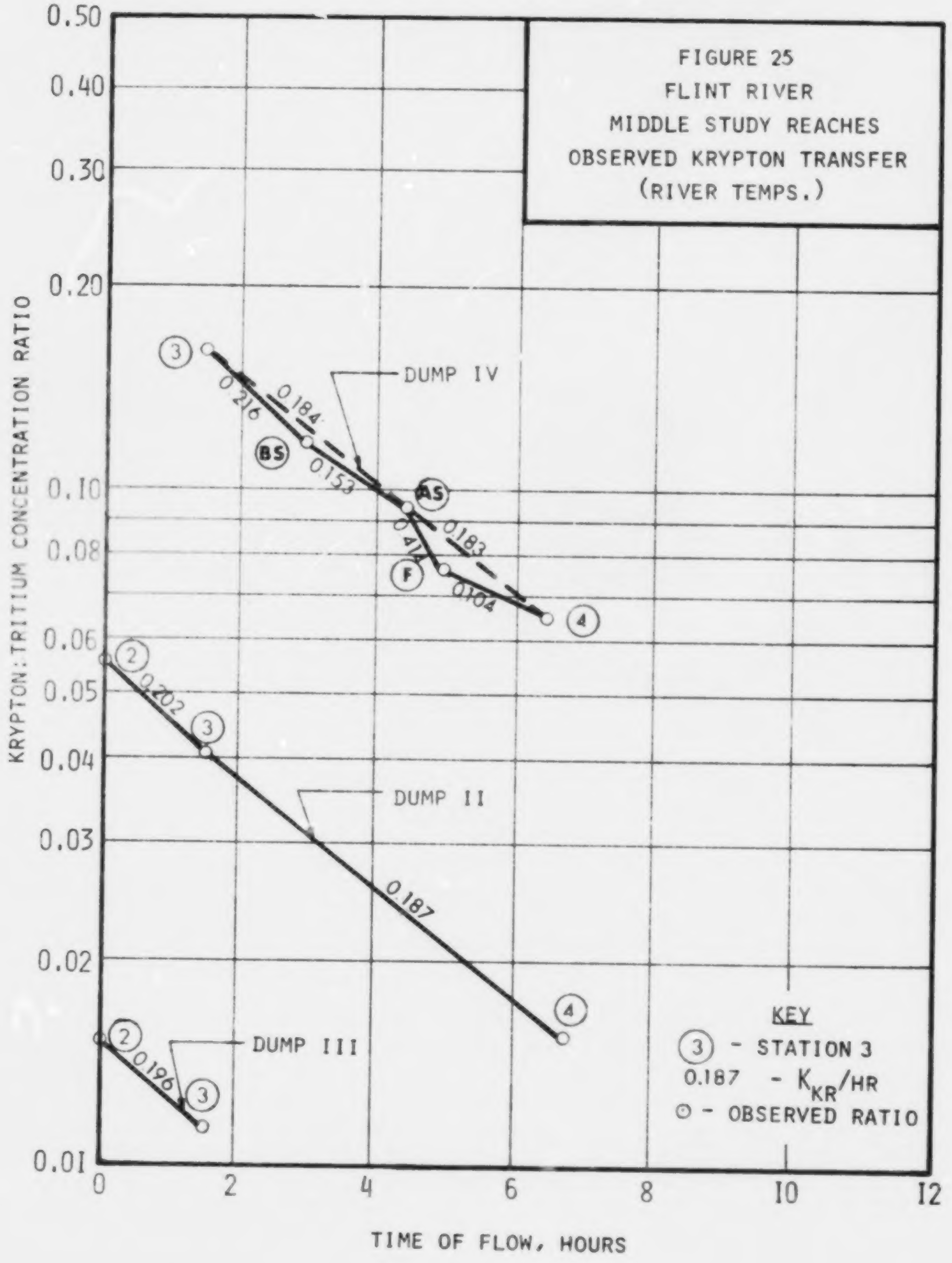


FIGURE 25
FLINT RIVER
MIDDLE STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

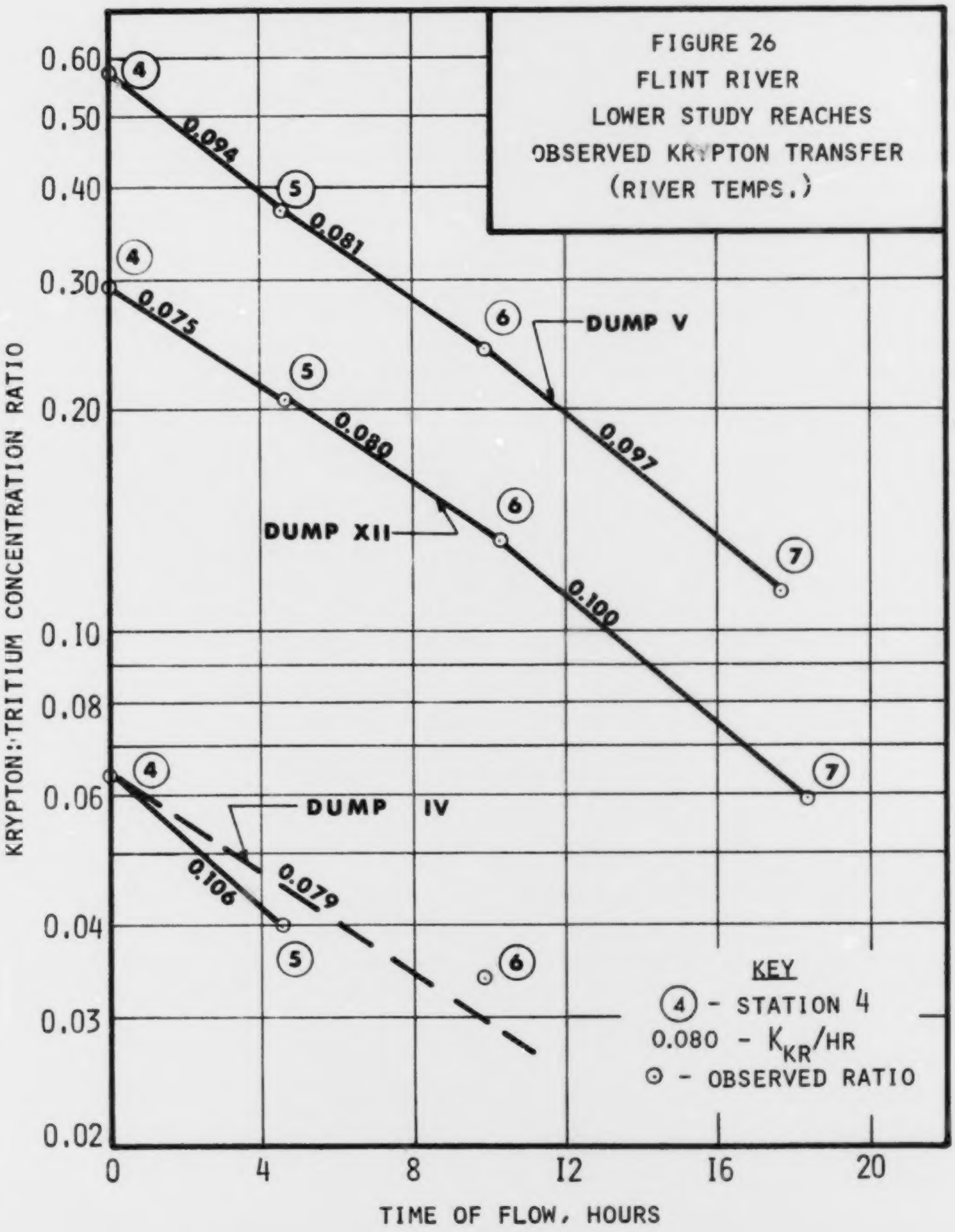


FIGURE 26
FLINT RIVER
LOWER STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

consistent results for the specific reaches, as do the observed values of K_{kr}. The observed krypton:tritium ratio for Station 6, Dump IV, is a dubious result due to poor counting statistics, as noted earlier. The loss of tracer gas for the whole reach 4-7 was remarkably consistent in Dumps V and XII, being 80.2 and 79.8 percent, respectively, over the 18-hour flow time. As indicated earlier, the Flint becomes somewhat larger below Station 4, and its general slope somewhat smaller. The preceeding Table of Typical Hydraulic Properties makes clear these and other significant features.

DO and BOD Results. The major pollution load received by the Flint River in the section included in these research studies came from the Flint River STP, the plant effluent entering the Flint about 200 feet above Station Number 0. During the 1969 research study period, the existing Flint River STP (trickling filter) was overloaded: the influent sewage flow averaged about 2.1 mgd, with an average 5-day BOD of 262 mg/l, and on the average, about 7 to 8 percent of this influent flow had to be bypassed. An additional smaller pollution load entered the Flint via Sullivan Creek immediately below Station Number 2: during the 1969 study period, the Sullivan Creek STP (trickling filter) treated an average influent flow of 0.82 mgd having a 5-day BOD of 191 mg/l, and accomplished an average BOD removal of 90 percent or a little better. Some additional pollution entered the Flint via Mud Creek (between Stations Number 3 and 4). Table 4 provides a summary of relevant information collected by the Georgia Water Quality Control Board[22].

Table 4

Flint River, 1969

Summary of DO and BOD Results

Location	Temperature °C	DO mg/l	BOD_5 mg/l
Above Flint River STP	14-24	5.4-8.8	3-9
Below Flint River STP	14-24	2.9-5.8	4-77
(Sullivan Cr)	(14-23)	(3.0-6.2)	6-18
Below station 2	15-24	1.8-5.2	16-55
Station 6	16-25	0.8-4.4	3-13

These results for the period April 30 - October 22, 1969, provide some indication of the highly variable nature of the

BOD load received by the Flint, but tell only part of the story. More recent information from the Georgia WQCB indicates clearly that both the Flint River STP effluent flow and its 5-day BOD may vary over quite a wide range during the 24 hours of any one day. In the upper reaches of the Flint, this plant effluent constitutes a major portion of the river flow. In addition, a substantial portion of the oxygen demand on the river results from the ammonia load present in the plant effluent. During the reaeration tracer studies available staff and equipment did not permit the extensive and thorough compositing of BOD samples that would be necessary for highly accurate oxygen balance analysis. Nor was the need for thorough analysis of samples for the nitrogen series foreseen. Hence, the BOD results presented below can be regarded only as a momentary representation of the quality of the Flint River, and it must be understood that the quality may very well have been significantly different a few hours earlier or later.

In addition to the foregoing problems associated with conducting an accurate oxygen balance, others are involved. Zero DO's were observed in the pools above both dams in the Flint River, and such results must be regarded as indeterminate for purposes of oxygen balance. No doubt, they were due in part to the presence of organic benthal deposits, especially in the pool above Station Number 1P. Also, growths of bacterial slimes and some algae were observed on rock surfaces between Stations Number 2P and 2, where a fraction of the river flowed over those rocks. A considerable number of the BOD-time series that were performed also displayed an erratic BOD process, typical of samples in which there is substantial nitrification.

As a result of the foregoing difficulties, some of which were not anticipated, no detailed oxygen balance has been attempted for the whole Flint River section studied, and, hence, only very limited evaluations of the DO effects of benthal decomposition and of the respiration of attached bacterial growths can be presented here.

Table 5 provides a summary of the DO and BOD data collected at the two waterfalls on the Flint during the gaseous tracer study periods, and these results do allow some limited estimates of interest here. Referring to Table 5, the observed 5-day BOD's at Station Number 1 and 2 were within the range usually observed by the Georgia WQCB, and were relatively high. At both waterfalls, reaches 1P-1 and 2P-2, substantial net DO increases were observed - an average of 3.4 mg/l in reach 1P-1 (typical time of flow 5 minutes) and 4.3 mg/l in reach 2P-2 (typical flow time 21 minutes). Within the limitations imposed by certain sources of uncertainty outlined below, comparison of the observed net gain of DO with the total DO gain obtained from the gaseous tracer data provides information of interest.

Table 5

Flint River, 1969

DO and BOD Results at Waterfalls

	DO, mg/l							
	1st Waterfall		2nd Waterfall		Temp, °C		BOD_5, mg/l	
Date (Dump)	1P	1	2P	2	1P-1	2P-2	1	2
4/25 (I)	0.0	3.3	0.0	3.9	17	13	nd*	nd
5/2 (II)	0.0	3.0	0.8	5.0	22	20	41	32
5/24 (III)	0.0	3.3	1.6	5.6	26	25	58	30
6/24 (--)	nd	nd	0.0	4.8	nd	23	nd	29
8/30 (XIV)	0.0	4.0	0.1	4.5	22	22	61	44

---

*nd: not determined.

Reference to equations (3), (7) and (11) of Section IV of this report indicates that

$$\log \left(\frac{D_B}{D_A}\right) = \frac{1}{0.83} \log \left(\frac{R_B}{R_A}\right) \qquad (41)$$

where A and B refer to upstream and downstream river sampling stations, respectively, D is the DO saturation deficit, in mg/l, and R is the krypton:tritium concentration ratio. Equation (41) may be used to evaluate the total DO added at the waterfalls. Any significant difference between the total DO added and the observed net DO increase reflects sources of oxygen consumption in the reach, assuming no significant errors of measurement.

Certain sources of error are present in the data. The DO and BOD samples could not usually be collected exactly at the time of arrival of the peak dye concentration at each station, as many other tasks had to be performed then, and, considering the highly variable BOD load in the river, this potential source of discrepancy may not always have been insignificant. Also, the krypton:tritium concentration ratios at Stations 1 and 2 are subject to some error due to low tracer gas concentrations resulting from the large gas losses over the waterfalls. DO's were analyzed by use of a Yellow

Springs instrument, as well as by the azide modification of the Winkler method, and some apparent differences in results were observed. Also, the data are not complete in every case - for example, although DO's were observed at Stations 1P and 1 for Dump II, the tracer release was made at Station 1, so there are no tracer gas transfer data for the reach 1P-1, Dump II.

Referring now to the reach 1P-1, krypton tracer data are available for Dumps III and XIV. Referring to the detailed tracer data in Appendix AIV, the average value of the ratio (R_1/R_{1P}) was 0.448, and, from equation (41), the ratio of saturation deficits is just 0.380. At the mean temperature of 24°C, and for an elevation of 880 feet above mean sea level, this indicates a total DO gain between Stations 1P and 1 of 5.1 mg/l. The observed net gain of DO was 3.7 mg/l, indicating DO consumption within the reach of about 1.4 mg/l. This estimate does not allow for any reduction in the effective value of DO saturation due to the presence of considerable pollution (5-day BOD of 60 mg/l), hence it is likely that the actual DO consumption between 1P and 1 was somewhat less than 1.4 mg/l, perhaps by 0.2 or 0.3 mg/l.

The reach 1P-1 is very shallow (a few inches deep) and swift, and the stream bed is largely rocks and stones. During these studies, extensive growths of bacterial slimes attached to the rocks were observed, together with relatively moderate to low quantities of blue green algae. That such bacterial growths can constitute an important source of oxygen consumption, even in a flow time as short as 5 minutes, is evident from the BOD data for Dumps III and XIV. Referring to Table 5, the average 5-day BOD's at Stations 1 and 2 were 60 and 37 mg/l, respectively; for these Dumps, the time of flow for the reach 1P-2 averaged 4.1 hours. There is no significant gain in streamflow between 1 and 2. The reduction from 60 mg/l to 37 mg/l in 4.1 hours leads to an average value of $(K_1)_{river}$ for the reach 1P-2 of about 0.12 per hour. The associated DO consumption for the reach 1P-1, even in a 5-minute time of flow, would be about 0.7 or 0.8 mg/l of DO. Furthermore, the observed $(K_1)_{river}$ of 0.12 per hour is an average value for the whole reach 1P-2, and it is likely that the actual magnitude of this rate coefficient was greater in short reaches like 1P-1 and lower in other pooled reaches between Stations 1 and 2, so that the estimated loss of 0.8 mg/l of DO in the reach 1P-1, due to attached oxidizing growths, may tend to be a somewhat low estimate. All such factors considered, a DO consumption of 1.0 mg/l between 1P and 1 due to respiration of attached oxidizing growths is regarded as a close estimate.

Similar computations may be made for the second waterfall, reach 2P-2. Krypton tracer data are available for Dumps II, III and XIV. The 5-day BOD's were lower for this reach, averaging about 35 mg/l for the three Dumps. More importantly, the reach 2P-2 is quite different in the hydraulic sense than the reach 1P-1, the reach below the second waterfall being pooled immediately below the falls (pool depth about 6 feet) and remaining relatively deep (about 2 feet) and slow above Station 2, with a stream bed of mud and sand. As a result, attached oxidixing growths do not occur in large amount between 2P and 2 except on the surfaces of elevated rocks at one side of the waterfall - only a small fraction (perhaps 10 percent) of the flow from Station 2P flows over these growths. Instead, there is ample opportunity for the accumulation of organic bottom deposits between 2P and 2, as well as in the larger pool above Station 2P. Although no specific observations were made, it is likely that bottom deposits of organic material between 2P and 2 were relatively small, as most of any settleable BOD load would have been deposited in the large pool above Station 2P.

The krypton tracer data indicate for the three Dumps an average value of 0.432 for the ratio (R_2/R_{2P}). From equation (41) and the data of Table 5, this indicates a total gain of DO between 2P and 2 of 4.9 mg/l. The net observed DO gain between the two stations averaged 4.2 mg/l, indicating sources of oxygen consumption between the two stations that utilized about 0.7 mg/l of DO. This is regarded as a good estimate of the combined effects of DO loss from the fraction of the stream flow that was exposed to the attached oxidizing growths and the DO loss from minor bottom organic deposits in the reach.

SOUTH RIVER

The South River originates in southwest Atlanta and forms part of the headwaters of the Altamaha River system. Like the Flint, the South flows through part of metropolitan Atlanta, and carries both domestic and industrial wastes as well as urban storm drainage. The South flows southeasterly approximately fifty miles before joining the Ocmulgee. The latter subsequently joins the Oconee to form the Altamaha, which then flows eventually into the Atlantic Ocean near Brunswick, Georgia.

The portion of the South River included in these studies extended from the South River STP to a point about one mile upstream from the intersection of the South River and Flat Bridge Road, a distance of 18.3 river miles. Figure 27 is a general map of the South River study locale, and shows salient features such as highways, tributary streams and the

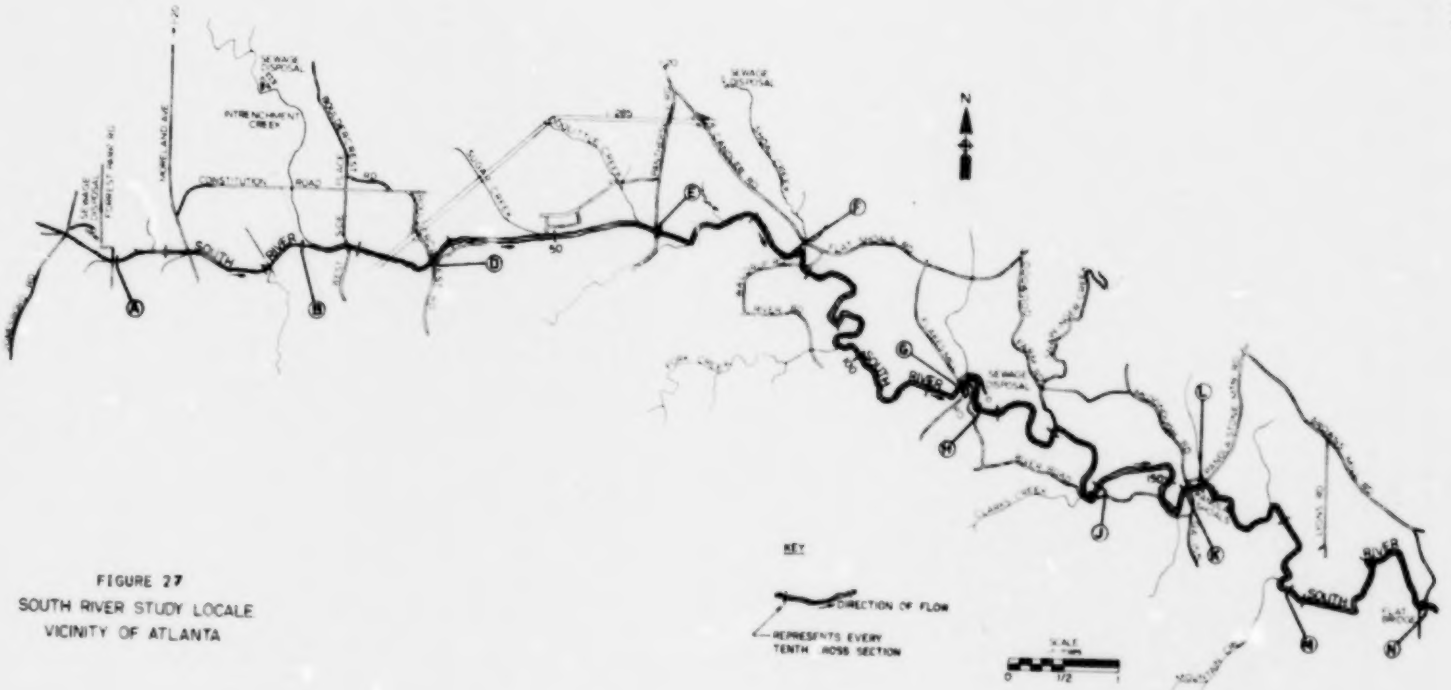

N
I-20
SEWAGE DISPOSAL
INTRENCHMENT CREEK
MORELAND AVE
FORREST PARK RD.
SEWAGE DISPOSAL
CONSTITUTION ROAD
BOULDERCREST RD
SUGAR CREEK
I-285
SEWAGE DISPOSAL
SOUTH
RIVER
SOUTH
RIVER
SOUTH
RIVER
50
100
150
A
B
D
E
F
G
H
J
K
L
M
N
SEWAGE DISPOSAL
CLARKS CREEK
FLAT BRIDGE
KEY
DIRECTION OF FLOW
REPRESENTS EVERY TENTH CROSS SECTION
SCALE
0
1/2
1

FIGURE 27
SOUTH RIVER STUDY LOCALE
VICINITY OF ATLANTA

river sampling stations. Within the 18-mile section studied, the South receives treated or partially treated domestic and industrial wastes from five treatment plants, namely, the Old and New South River STP's at the upper end, the Intrenchment Creek STP, the Shoal Creek STP and the Snapfinger STP, as well as from other sundry sources. All of these wastes enter the stream above Panola Shoals. The South was heavily polluted, as a result, throughout the entire study section. Large quantities of floating foam were seen frequently, especially in a pool immediately below Panola Shoals.

The South River channel is relatively uniform. A typical section in the upper third of the 18-mile study section is thirty to forty feet wide and one to two feet deep. The width and depth increase proceeding further downstream, but the depth:width ratio remains fairly constant. The channel is relatively straight, with high steep banks. The bottom material is primarily sand. There are occasional pools followed by short reaches of rapids, but the predominant characteristic of the channel is its uniformity. The most unusual hydraulic feature occurs at Panola Shoals, where the water flows in thin sheets over large smooth granitic rocks, falling about eight feet in a matter of about 30 yards. The largest and deepest pool is located immediately above Panola Shoals. The river attains a width of approximately 100 feet, with depths of six to seven feet, in this pool.

Dosing Pattern. Table 6 shows the dosing pattern that was used in the 1969 tracer studies of gas transfer in the South River. This pattern of eight separate releases was designed to provide at least two separate measures of gas transfer in each of the subreaches, to verify reproducibility; in the case of reach K-L (Panola Shoals) four separate observations of K_{kr} were made. As may be seen, the quantities of tracer were varied somewhat, the krypton-85 dose ranging from 296 mc to 597 mc and the tritium dose from 349 mc to 826 mc. A total of 2.93 curies of krypton-85 and 3.47 curies of tritium were released in the eight South River tracer studies.

The study locale map, Figure 27, shows the location of the sampling stations listed in Table 6, and Table AI.2, in Appendix AI, provides more detailed station descriptions. The stream sampling stations were selected both for relationship to hydraulic features of interest and for accessibility.

Hydraulic Properties. Table 7 summarizes the typical hydraulic properties of the sections studied. These typical results represent field measurements of relevant hydraulic features at 500-foot intervals, as described earlier. The detailed hydraulic properties are provided in Appendix AIII.

Table 6

Dosing Pattern, South River

Dump Number	South River Sampling Station Number											
	A	B	D	E	F	G	H	J	K	L	M	N
VI ...	6/16	...	...	...	...	...	...	...	...	...	...	...
	323	...	...	...	...	...	...	...	...	...	...	...
	349	...	...	...	...	...	...	...	...	...	...	...
VII	...	...	...	...	...	6/18	...	...	...	...	...	...
						330	...	...	...	...	...	...
						380	...	...	...	...	...	...
VIII	...	...	...	...	...	...	...	6/20	...	...	...	...
								345	...	...	...	...
								370	...	...	...	...
IX	...	...	...	6/23	...	...	...	...	...	...	...	...
				305	...	...	...	...	...	...	...	...
				387	...	...	...	...	...	...	...	...
X ...	6/25	...	...	...	...	...	...	...	...	...	...	...
	311	...	...	...	...	...	...	...	...	...	...	...
	357	...	...	...	...	...	...	...	...	...	...	...
XI	...	...	...	...	6/27	...	...	...	...	...	...	...
					296	...	...	...	...	...	...	...
					370	...	...	...	...	...	...	...
XIII	...	...	...	...	...	...	...	8/27	...	...	...	...
								597	...	...	...	...
								432	...	...	...	...

Table 6 (continued)

Dosing Pattern, South River

Dump Number	South River Sampling Station Number											
	A	B	D	E	F	G	H	J	K	L	M	N
XV	......	......	......	......	9/26	......	......	......	......	......	......	......
					421	......	......	......	......	......	......	......
					826	......	......	......	......	......	......	......

Key: 6/16 - Dump VI released 6/16/69 at Station A
323 - 323 mc krypton-85 released
349 - 349 mc tritium released

Figure 28 shows the channel profile for the South River reach studied.

As indicated above, the South River channel is relatively uniform, with few exceptional features. Flow throughout the study reach varies somewhat depending upon effluent flows from the several waste treatment plants and from the tributary streams. A substantial rapids section occurs in the upper portion of the reach G-H, and was the subject of special investigation in Dump XV. The reach J-K includes the large deep pool above Panola Shoals. This pool is about 800 feet long, with depths up to six or seven feet, and a typical observed flow-through time of about 2.5 hours. As will be shown below, the observed results indicate that the incoming flow often does not mix completely with the pool contents - this incomplete mixing phenomenon is apparently the rule, rather than the exception, in this pool. The natural rock barrier at the lower end of the pool (Station K) develops gradually, rather than being like a vertical dam wall, and the pool depth decreases gradually toward this barrier, rather than being at its deepest at Station K. As a result, depending upon other factors such as the temperature differential between the pool contents and the incoming river flow, the rate of inflow, etc., at some times the flow over the barrier at Station K may be largely pool surface water and at other times may be primarily bottom water from the pool depths.

The reach K-L includes Panola Shoals, where the flow spreads thinly over wide smooth granitic rock surfaces to fall approximately eight feet into a small mixing basin or pool. The time of flow for this reach is about 12 minutes, during which, as will be seen, considerable gas transfer occurs.

Reaeration Coefficients. Table 8 provides a summary of all of the reaeration coefficients observed in the South River studies, for the main study reaches. The South River studies included eight separate tracer releases (Dumps VI, VII, VIII, IX, X, XI, XIII, XV) as shown, and 85 separate main reach values of K_{ox} were obtained. In most cases at least two separate values of K_{ox} were obtained for the same reach, and in some cases, notably the reaches G-H, H-J, J-K, and K-L, four or more tests were conducted.

Reference to Table 8 indicates that reproducibility of the test results was generally very good. The South River channel profile is not so steep as the Flint River profile, and the channel is considerably more uniform. It is similar to the Lower Study Reaches of the Flint. The observed K_{ox} values are correspondingly lower, in the general neighborhood

Table 7

Typical Hydraulic Properties

South River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft	Bottom* Char
VI	A-B	47	2.48	10,250	1.15	1.05	40	12.1	Sand, mud
"	A-D	62	3.85	16,250	1.17	1.30	53	24.0	" "
"	A-E	73	6.28	27,650	1.22	1.29	59	36.5	"
"	A-F	76	7.98	36,650	1.27	1.21	60	44.8	"
VI	B-D	63	1.37	6,000	1.21	1.51	52	11.9	Sand
"	B-E	74	3.80	17,400	1.27	1.40	58	24.4	"
"	B-F	78	5.50	26,400	1.33	1.37	58	32.7	"
VI	D-E	89	2.43	11,400	1.30	1.34	68	12.5	Sand, rock
"	D-F	92	4.13	20,400	1.37	1.30	68	20.8	"
IX	E-F	72	1.78	9,000	1.40	1.39	51	8.6	Sand
"	E-G	80	6.53	27,400	1.16	1.64	69	24.2	"
"	E-H	83	7.17	30,200	1.17	1.67	71	31.3	" , rock
"	E-J	113	10.60	40,600	1.06	1.75	107	45.5	" "
"	E-K	115	13.82	49,200	0.99	1.84	116	47.7	" "
IX	F-G	82	4.75	18,400	1.07	1.81	77	15.6	Sand, rock
"	F-H	86	5.38	21,200	1.09	1.78	79	22.7	" "
"	F-J	116	8.82	31,600	1.00	1.85	116	36.9	" "
"	F-K	118	12.03	40,200	0.93	1.94	127	39.2	" "
VII	G-H	124	0.43	2,800	1.81	1.90	69	7.7	Rock
"	G-J	139	3.55	13,200	1.03	1.97	135	21.9	" , sand
"	G-K	141	6.82	21,800	0.89	1.82	158	24.0	" "
"	G-L	141	7.00	22,300	0.88	2.12	160	36.2	" "

Table 7 (continued)

Typical Hydraulic Properties

South River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft	Bottom* Char
VII	H-J	139	3.12	10,400	0.93	2.10	149	14.2	Sand, rock
"	H-K	141	6.38	19,000	0.83	2.12	170	16.4	" , mud
"	H-L	141	6.57	19,500	0.82	2.15	172	28.5	
VIII	J-K	188	2.72	8,600	0.88	2.40	214	2.1	Sand, mud
"	J-L	188	3.00	9,100	0.84	2.32	224	14.3	" "
"	J-M	196	4.85	18,000	1.03	2.02	190	19.0	" "
"	J-N	198	7.30	25,500	0.97	1.86	204	28.0	" "
VIII	K-L	190	0.28	500	0.50	1.67	380	12.2	" "
"	K-M	198	2.13	9,400	1.22	1.88	162	16.9	Sand, "
"	K-N	200	4.58	16,900	1.02	1.58	196	25.9	" "
VIII	L-M	198	1.85	8,900	1.34	1.70	148	4.7	Sand, mud
"	L-N	200	4.30	16,400	1.05	1.58	190	13.7	" "
VIII	M-N	207	2.45	7,500	0.85	1.43	243	9.0	Sand, mud

---

*Predominant bottom character.

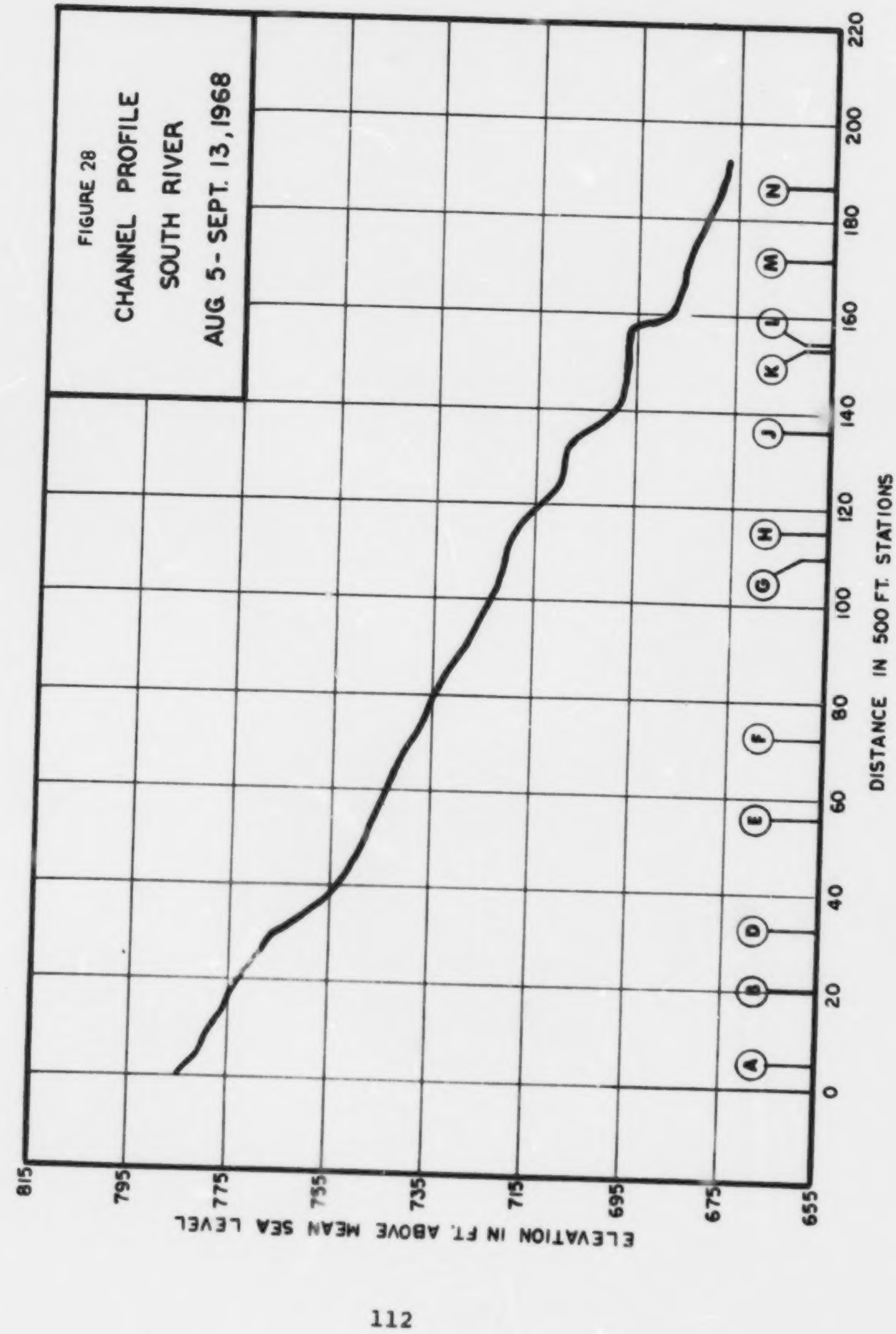


FIGURE 28
CHANNEL PROFILE
SOUTH RIVER
AUG 5 - SEPT. 13, 1968

Table 8

Observed Reaeration Coefficients, South River

Main Study Reaches

Reach	K_{ox} per hour @ 25°C								
	VI	VII	VIII	IX	X	XI	XIII	XV	Mean
A-B	0.244	-	-	-	0.164	-	-	-	0.204
A-D	0.285	-	-	-	0.208	-	-	-	0.247
A-E	0.252	-	-	-	0.182	-	-	-	0.217
A-F	0.240	-	-	-	0.184	-	-	-	0.212
B-D	0.358	-	-	-	0.289	-	-	-	0.324
B-E	0.258	-	-	-	0.194	-	-	-	0.226
B-F	0.238	-	-	-	0.192	-	-	-	0.215
D-E	0.204	-	-	-	0.144	-	-	-	0.174
D-F	0.200	-	-	-	0.162	-	-	-	0.181
E-F	0.194	-	-	0.178	0.188	-	-	-	0.187
E-G	-	-	-	0.150	-	-	-	-	-
E-H	-	-	-	0.179	-	-	-	-	-
E-J	-	-	-	0.205	-	-	-	-	-
E-K	-	-	-	0.188	-	-	-	-	-
F-G	-	-	-	0.139	-	0.111	-	-	0.125
F-H	-	-	-	0.180	-	0.168	-	-	0.174
F-J	-	-	-	0.211	-	0.212	-	-	0.212
F-K	-	-	-	0.189	-	0.177	-	-	0.183
G-H	-	(0.920)*	-	0.482	-	0.592	-	0.528	0.534
G-J	-	o.336	-	0.294	-	0.326	-	0.296	0.313
G-K	-	0.173	-	0.222	-	0.216	-	0.180	0.198
G-L	-	0.283	-	-	-	-	-	0.263	0.273

---

*Questionnable result - not included in mean.

Table 8 (continued)
Observed Reaeration Coefficients, South River
Main Study Reaches

Reach	K_{ox} per hour @ 25°C								
	VI	VII	VIII	IX	X	XI	XIII	XV	Mean
H-J	-	0.255	-	0.260	-	0.279	-	0.263	0.264
H-K	-	0.122	-	0.197	-	0.183	-	0.157	0.165
H-L	-	0.241	-	-	-	-	-	0.246	0.244
J-K	-	(-0.004)*	(0.119)*	(0.131)*	-	(0.093)*	(0.028)*	(0.067)*	(0.072)*
J-L	-	0.228	0.237	-	-	-	0.219	0.231	0.229
J-M	-	-	0.171	-	-	-	0.172	-	0.172
J-N	-	-	0.154	-	-	-	0.173	-	0.164
K-L	-	(4.31)*	(1.37)*	-	-	-	(3.25)*	(2.92)*	(2.96)*
K-M	-	-	0.237	-	-	-	0.373	-	0.305
K-N	-	-	0.175	-	-	-	0.265	-	0.220
L-M	-	-	0.066	-	-	-	0.096	-	0.081
L-N	-	-	0.098	-	-	-	0.141	-	0.120
M-N	-	-	0.122	-	-	-	0.175	-	0.149

---

*Questionnable result

of 0.2 per hour at 25°C, with a low of perhaps 0.03 or 0.05 per hour in the pool above Panola Shoals to a high of about 3.0 per hour over Panola Shoals.

As noted earlier, the South is heavily polluted from four separate sources, and this in itself brings about some variability of reaeration capacity. This is best exemplified by comparing the observed results for Dumps VI and X, both of which included the reach A-F. Both studies were at the same river flow and essentially the same temperature. Yet the observed values of K_{ox} for Dump VI were consistently significantly higher than the Dump X values. The subject of pollutant effects on reaeration capacity will be discussed in greater detail subsequently, but is noted here in terms of this particular set of observed results.

The reach G-H, containing the rapids section at its upper end, had a K_{ox} of about 0.53 per hour at 25°C. Dump XV, a more detailed study, yielded an observed K_{ox} 1.28/hour at 25°C for the rapids itself, where most of the elevation change occurred.

The results for the reach J-K, containing the pool above Panola Shoals, are quite variable compared to any other reach studied in any of the river studies reported here. In six separate studies covering this reach the value observed for K_{ox} at 25°C varied from 0.00 per hour (-0.004) to 0.13 per hour. Without doubt, this high degree of variablilty is the result of the erratic and incomplete mixing of the incoming flow and the pool contents, as noted earlier, together with the bottom or top water release at Station K. The mean observed K_{ox} of 0.07 per hour at 25°C is judged to be probably somewhat high.

Because Station K cannot be taken always to be representative of the whole South River flow, as outlined earlier, the observed values of K_{ox} for Panola Shoals, reach K-L, are also more variable than usual. The four observed values ranged from 1.4 to 4.3 per hour at 25°C. The mean of 3.0 per hour is regarded as a close estimate of the reaeration capacity of the Shoals.

The remarkable consistency of the four observed values of K_{ox} for the reach J-L, which includes both the pool (J-K) and the Shoals (K-L), provides ample evidence of the validity of the foregoing outline of hydraulic reasons for the variability of results in the pool and over the Shoals when taken separately. For the whole reach J-K the four observed values of K_{ox} ranged only from 0.219 to 0.237 per hour, and the mean of 0.229 per hour at 25°C is thus seen to be highly accurate.

Stations J and L were quite representative of the whole flow, but Station K was very sensitive to the momentary hydraulic conditions in the pool.

Figures 29 and 30 are a graphical presentation of the results for the South River studies, and illustrate the foregoing. The numerical values of K_{kr} shown on the graphs refer to the prevailing river water temperatures and flows at the time of the individual tracer releases, and the values of K_{ox} presented in the preceeding Table 8 have been obtained by use of the basic K_{kr}:K_{ox} ratio of 0.83 and the temperature coefficient of 1.022/°C.

Referring now to Figure 29, for the Upper Study Reaches, the generally parallel nature of the lines is evident. As noted earlier, although Dumps VI and X were performed at essentially the same flow and water temperature, the observed values of K_{kr} were consistently higher in Dump VI, indicating a different pollutant effect.

Reference to Figure 30 (Lower Study Reaches) illustrates the behavior of the rapids section in the reach G-H, the long deep pool in the reach J-K, and the rapid change of elevation at Panola Shoals, reach K-L. As outlined earlier, mixing of the inflowing water with the pool contents was erratic and nonhomogeneous in the reach J-K, leading to a wide range of observed values of K_{kr}. In contrast, the four observed values of K_{kr} in the reach H-J, immediately upstream, were quite consistent (0.255 to 0.279 per hour at 25°C). The four observed values of K_{kr} for the reach J-L ranged only from 0.171 to 0.192 per hour, and led to the equally consistent set of results for K_{ox} at 25°C (0.219 to 0.237 per hour) noted above.

DO and BOD Results. In the 18.3 mile section of the South River included in these research studies, the stream receives wastes from five municipal treatment facilities and from 16 smaller sources[22]. The five municipal plant effluents are from the Old South River STP (trickling filter, 6.0 mgd) and the New South River STP (modified activated sludge, 12.0 mgd), both located above Station A, the Intrenchment Creek STP (high rate trickling filter, 20 mgd) just below Station B, the Shoal Creek STP (trickling filter, 3.0 mgd) just below Station F, and the Snapfinger Creek STP (trickling filter, 2.0 mgd in 1969) below Station H. The Snapfinger Creek STP was greatly overloaded in 1969; it was expanded to 6.0 mgd capacity in 1970, but was still overloaded at times.

The operation of these waste treatment plants was evaluated

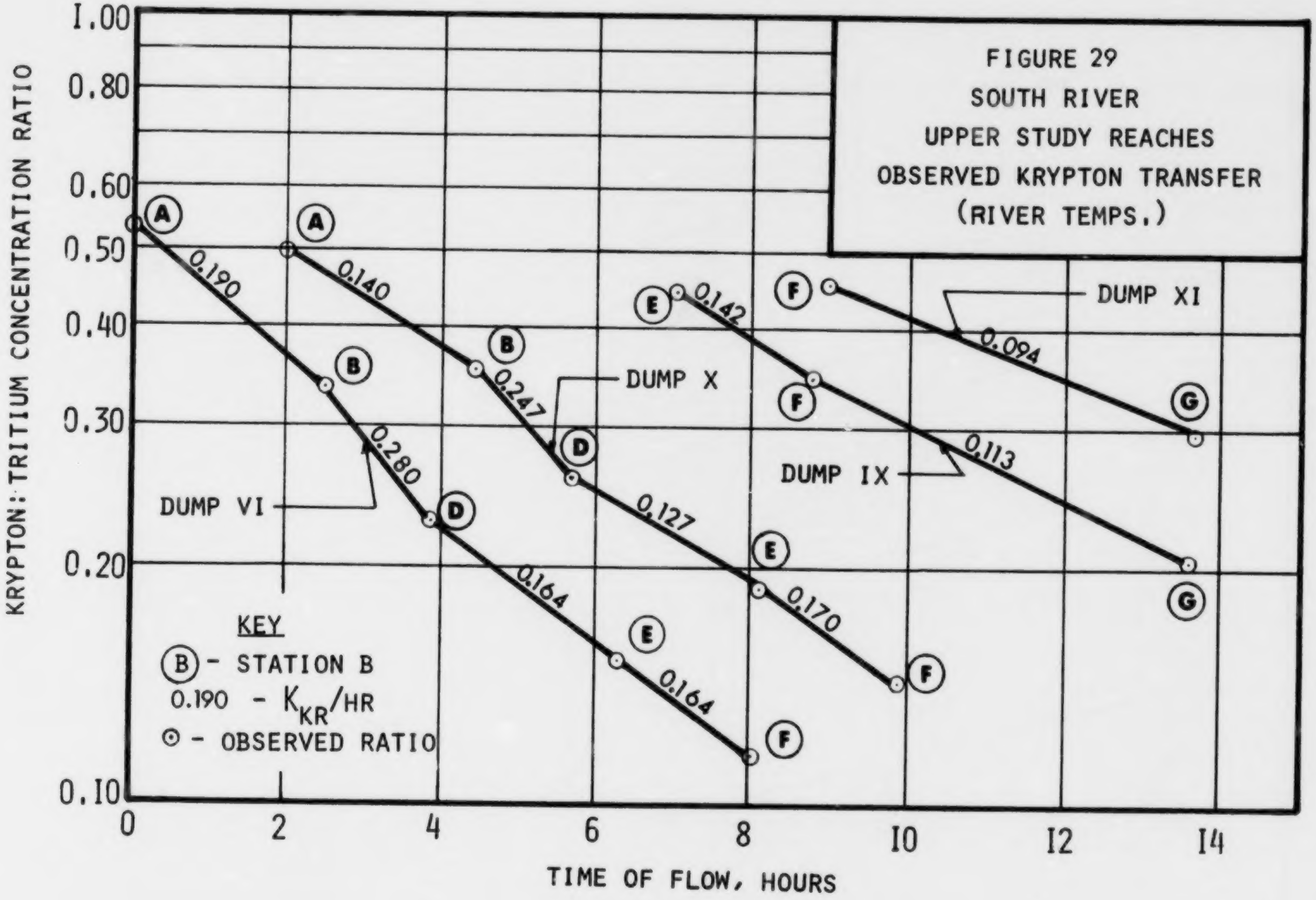


FIGURE 29
SOUTH RIVER
UPPER STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

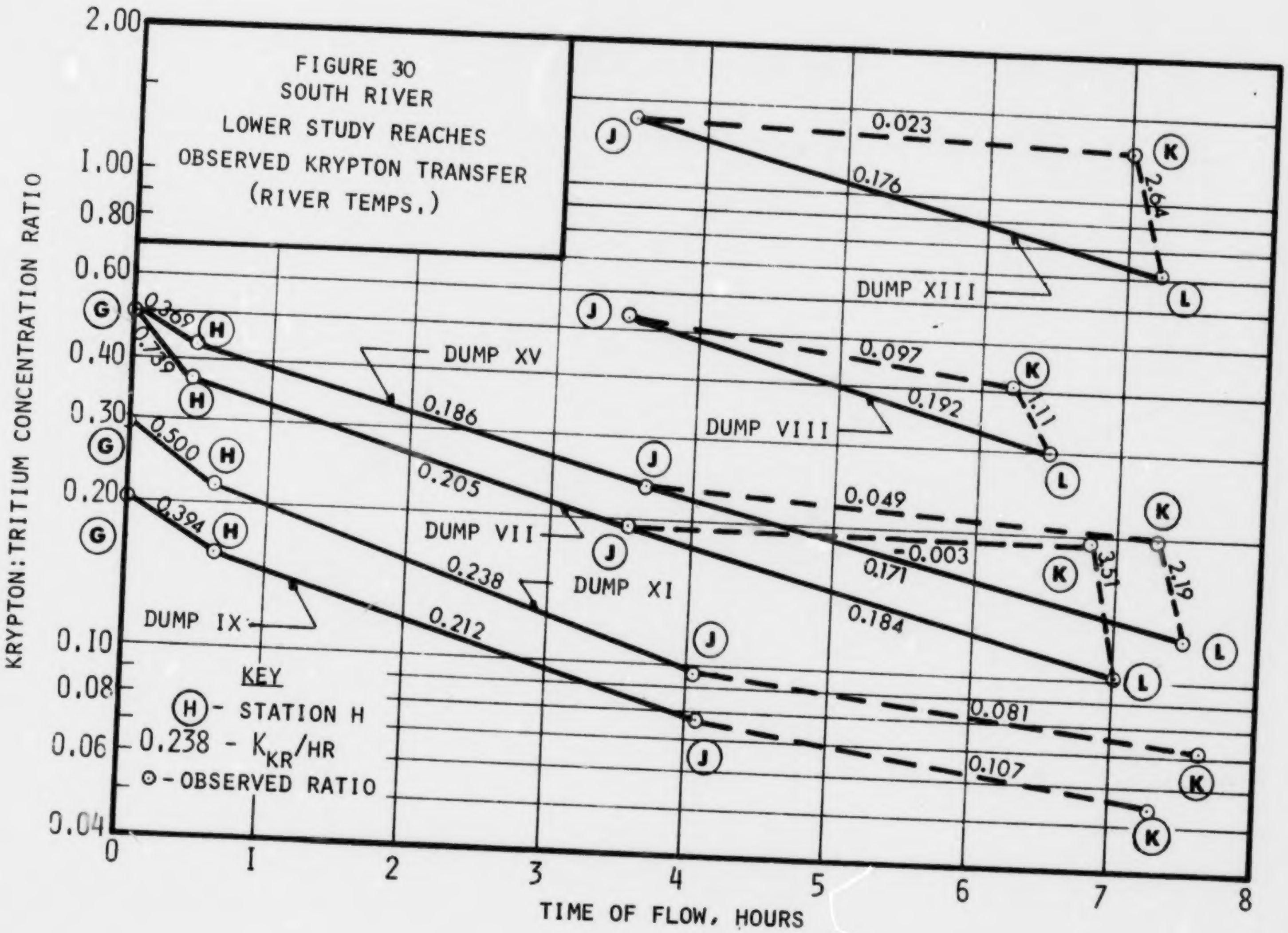


FIGURE 30
SOUTH RIVER
LOWER STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

in 1970 by the Georgia WQCB[23]. During 1970, the total waste flow from the five plants was 40.1 mgd. The BOD_5 released to the South River totalled 13,300 lbs/day from the five plants, and the total ammonia nitrogen discharge averaged 3,150 lbs/day. These records of the Georgia WQCB indicate that "The highest organic nitrogen (including ammonia) concentrations observed in the river occurred below the confluence with Snapfinger Creek" (between Stations H and J). Table 9 provides a summary of relevant information reported by the Georgia WQCB for the period April 23 - October 9, 1969[22].

Table 9

South River, 1969

Summary of DO and BOD Results

Location	Temperature °C	DO mg/l	BOD_5 mg/l
Above South R STP (Above Sta A)	13-23	6.3-8.8	1-14
US Hwy 23 (Below Sta A)	14-26	2.6-6.8	15-27
(Intrenchment Crk)	(16-25)	(2.5-4.9)	(21-40)
Bouldercrest Rd (Sta D)	15-25	2.4-4.8	9-36
Panthersville Rd (Sta E)	15-25	2.4-4.8	12-33
Ga Hwy 155 (Sta L)	15-25	5.2-7.8	6-20
Ga Hwy 138 (Below Sta N)	15-26	4.3-8.0	4-10

It is evident from the foregoing data that the South River was heavily polluted during the 1969 research study period, and that there was considerable variability of DO and BOD. The multiple sources of pollution, the variability of loads and the variability of flows in the river made accurate oxygen balance studies for the whole 18.3 mile section a project beyond the planned scope and the physical capability of the research staff. In addition, the presence of large amounts of organic nitrogen in the river led again to highly erratic BOD-time series because of the occurrence of nitrification. As a result, no detailed oxygen balance for the whole South River study section is presented here. However, the DO and BOD results obtained on separate occasions at Panola Shoals provide interesting information. Those results are summarized in Table 10.

Table 10

South River, 1969

DO and BOD Results at Panola Shoals

Date (Dump)	DO, mg/l K	DO, mg/l L	Temp °C	BOD_5 mg/l
6/18 (VII)	2.8	5.1	22	7.9
6/27 (XI)	2.5	6.0	26	12
8/28 (XIII)	1.9	5.6	23	9.4

Referring to Table 10, the observed 5-day BOD's were within the range usually found by the Georgia WQCB, and were not especially high. For the three Dumps, the observed average net gain of DO over the Shoals, reach K-L, was 3.2 mg/l, in an average flow time of 12 minutes. Krypton tracer data are available for Dumps VII and XIII (see Appendix A IV), and provide an average value for the ratio (R_L/R_K) of 0.544. At the mean river water temperature of 22.5°C and for an elevation of 700 feet above mean sea level, application of equation (41) indicates a total DO gain between Stations K and L of 3.2 mg/l. The observed net DO gain for Dumps VII and XIII averaged 3.0 mg/l, for comparison, as against the average observed net DO gain of 3.2 mg/l for all three dates.

The stone surfaces of the Shoals between Stations K and L were covered by prolific growths of both algae and bacteria during these research studies, and most of the water flowed over these growths in relatively thin sheets of flow. There can be no doubt that the DO concentration of the flowing water was affected both by the photosynthetic activity of the algae and the respiration of the attached bacteria - in essence, between K and L there was a major source of DO replenishment as well as a major source of DO consumption. The analysis presented above indicates that these processes were in near-balance, so far as DO change was concerned - that is, that about as much DO was added by photosynthesis as was lost due to respiration.

PATUXENT RIVER

The Patuxent River below Laurel, Maryland, is a typical relatively small coastal plains stream, nontidal, and characterized by alternating small pools and gentle riffles. Studies of its reaeration capacity were performed in September, 1969, for the Maryland Department of Water Resources as a part of that Agency's program for protection of the quality of the stream.

The reach of stream covered by these reaeration studies included the critical 7-mile section from the Laurel, Maryland, Sewage Treatment Plant (secondary treatment), through the USDI Patuxent Wildlife Refuge, to a location above Bowie, Md. At critical low summer flows the stream depths are relatively shallow, velocities slow for the most part, and the stream meanders quietly through the Wildlife Refuge. At somewhat higher flows, the stream splits into multiple channels at several locations in the Refuge.

Figure 31 is a map of the section studied, and depicts the general area, the Wildlife Refuge boundary, location of stream sampling stations and other relevant features. The typical reach between sampling stations was about one mile in length, or a little more. At the critical low flows that prevailed during the tracer study period, the depth of flow ranged from four to six inches in the riffles to perhaps as much as two feet in the deeper pools. The typical riffle was perhaps 20 to 30 feet in length, with a bottom of small (three-to five-inch) rounded smooth stones. Most of the pools were relatively short and shallow (one foot to 1-1/2 feet deep) and had a mud and silt bottom. Exceptions were the longer, deeper pool at Duvall Bridge (Station 4) and the somewhat deeper flows at the lower end of the study section.

Dosing Pattern. Table 11 shows the pattern of tracer doses that was used in the 1969 studies of gas transfer and reaeration in the Patuxent River. The pattern of five separate tracer releases provided a measure of gas transfer in each of the subreaches at least twice. The quantities of tracer used were fairly uniform, except for the quantity of tritium in Dump E, and averaged 376 mc of krypton-85 and 519 mc of tritium. A total of 1. 879 curies of krypton-85 and a total of 2.595 curies of tritium were released in the five doses.

Hydraulic Properties. Table 12 provides a summary of typical hydraulic properties of the Patuxent River study reaches. As may be seen, the range of typical velocities and depths is small compared to similar results for the Flint and South Rivers. The range of slopes is also relatively small, and typical velocities are lower. No remarkable hydraulic features such as violent rapids, falls or shoals occurred in the Patuxent River study section. This indicates a higher degree of hydraulic uniformity than in the Flint or South,

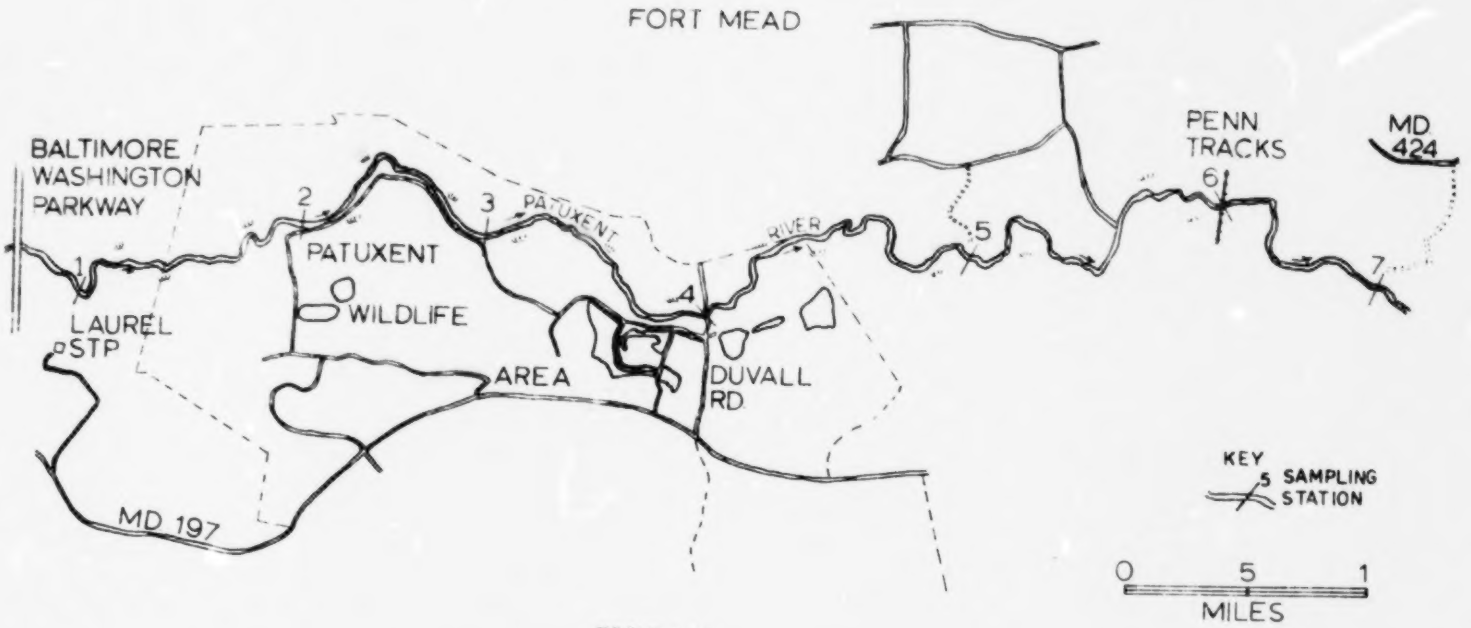

FORT MEAD
BALTIMORE WASHINGTON PARKWAY
1
2
3
4
5
6
7
PATUXENT
RIVER
PATUXENT WILDLIFE AREA
LAUREL STP
DUVALL RD
MD 197
PENN TRACKS
MD 424
KEY
5 SAMPLING STATION
0
5
1
MILES

FIGURE 31
PATUXENT RIVER STUDY LOCALE

Table 11

Dosing Pattern, Patuxent River

Dump Number	Patuxent River Sampling Station Number 1	2	3	4	5	6	7
A				9/5 342 458			
B	9/6 349 443						
C				9/8 398 479			
D	9/9 362 489						
E				9/11 428 726			

Key: 9/5 - Dump A released on 9/5/69 at Station 4
342 - 342 mc of kyrpton-85 released
458 - 458 mc of tritium released

Table 12
Typical Hydraulic Properties
Patuxent River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft	Bottom* Char
B	1-2	9.8	3.85	5,400	0.39	0.80	25	7.0	Mud, sand
"	1-3	9.8	9.08	9,600	0.29	0.90	34	11.9	" "
"	1-4	9.8	14.75	16,800	0.32	0.90	31	21.9	" "
B	2-3	9.8	5.23	4,200	0.22	1.00	45	4.8	" "
"	2-4	9.8	10.90	11,400	0.29	1.00	34	14.9	" "
B	3-4	9.8	5.67	7,200	0.35	1.00	28	10.1	" "
A	4-5	19.5	6.70	8,400	0.35	1.10	56	14.7	" "
"	4-6	19.5	13.92	15,000	0.30	1.10	65	23.2	" "
"	4-7	19.5	17.52	19,800	0.31	1.10	63	29.6	" "
A	5-6	19.5	7.22	6,600	0.25	1.10	78	8.5	" "
"	5-7	19.5	10.82	11,400	0.29	1.05	67	14.9	" "
A	6-7	19.5	3.60	4,800	0.37	1.00	53	6.4	" "

---

* Predominant bottom character

as a result of which a more narrow range of reaeration rate coefficients, K_{ox} at 25°C, may well be expected.

Flows were measured by Maryland DWR personnel during the course of the tracer studies. They exhibited substantial short term fluctuations during the study period, and, for that matter, during certain of the individual tracer release periods. For example, observed flows at Duvall Bridge (Station 4) varied from about 7 to 16 cfs during the study period, and individual flow observations ranged from 7 to 23 cfs over the whole study section. Occasional local rains during tracer studies also brought about some variability of stream flow.

The stream physical studies were performed by Maryland DWR personnel in late 1969, after the tracer studies were complete, and included discharge, elevation and cross-sectional measurements at about 600-foot intervals. As prevailing stream flows were significantly higher than those during the September tracer study period, hydraulic properties that prevailed during the tracer studies were obtained by adjusting the physical study data accordingly.

In addition to the flow measurements and stream physical studies, personnel of the Maryland DWR were also primarily responsible for the conduct of Dump E, the last tracer release.

Reaeration Coefficients. All of the reaeration coefficients obtained in the Patuxent River studies are summarized in Table 13. Duplicate values were obtained for the upper study section (above Station 4) and triplicate values below Station 4. Figure 32 is a graphical presentation of all of the observed gas transfer results for the Patuxent, the results for Dumps C, A and E having been displaced successively to the right on the graph in order to avoid overlapping or crossing of lines. The values of K_{kr} shown in Figure 32 represent the prevailing river temperatures (see Appendix AIV for details). The values of K_{ox} presented in Table 13 have been derived from the basic K_{kr}/K_{ox} ratio of 0.83 and corrected to 25°C by use of the temperature correction coefficient 1.022/°C.

Reference to Table 13 and to Figure 32 again indicates good reproducibility of results, although the data for Dump E appear to depart more than usual from the results for Dumps A and C. Reproducibility of the observed values of K_{ox} at 25°C was excellent between Dumps A and C (below Station 4), and very good between Dumps B and D (above Station 4). Dump E took place at a lower flow than Dumps A and C, as indicated

Table 13

Observed Reaeration Coefficients, Patuxent River

Reach	K_{ox} per hour @ 25°C					
	A	B	C	D	E	Mean
1-2	-	0.159	-	0.167	-	0.163
1-3	-	0.122	-	0.145	-	0.134
1-4	-	0.122	-	0.149	-	0.136
2-3	-	0.095	-	0.131	-	0.113
2-4	-	0.109	-	0.143	-	0.126
3-4	-	0.123	-	0.155	-	0.139
4-5	0.141	-	0.160	-	0.135	0.145
4-6	0.129	-	0.129	-	0.108	0.122
4-7	0.150	-	0.151	-	0.114	0.138
5-6	0.118	-	0.101	-	0.084	0.101
5-7	0.156	-	0.145	-	0.101	0.134
6-7	0.234	-	0.227	-	0.136	0.199

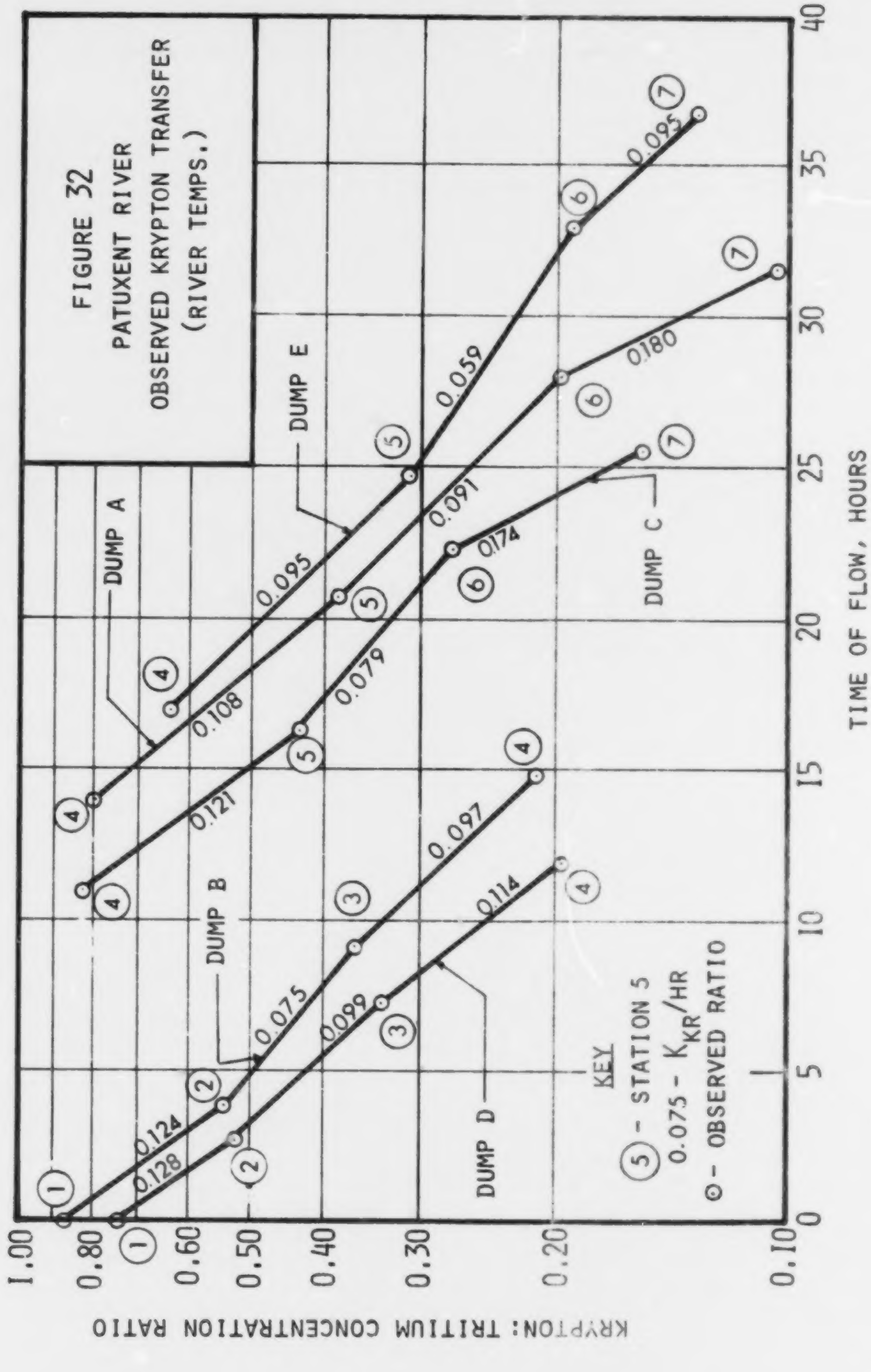


FIGURE 32
PATUXENT RIVER
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

by the somewhat longer times of flow, which may account in part for the lower values of K_{ox} observed for Dump E. As indicated above, substantial fluctuations in river flow also occurred during some of the studies.

Reference to Table 13 indicates a high degree of uniformity of results for the whole section of the Patuxent that was studied. Neglecting Dump E for the moment, all of the individual values of K_{ox} at 25°C fall within the range of 0.10 to 0.23 per hour; except for the reach 6-7, the range of observation is only 0.10 to 0.17 per hour, and the range of mean values is only 0.11 to 0.16 per hour. This consistency of results clearly shows the effect on K_{ox} of the higher degree of hydraulic uniformity referred to earlier. Considering the flow variations that occurred during these tracer studies, in the case of this section of the Patuxent between Stations 1 and 6, no major error would be made by selecting a single value of K_{ox} for use in oxygen balance computations in the same range of flow.

JACKSON RIVER

The Jackson River has its source in the mountains of Virginia and West Virginia, and flows generally east and southeast through Covington and Clifton Forge, Va. Below Clifton Forge it joins the Cowpasture River and becomes the James, which then flows past Lynchburg to the ocean at Norfolk, Va. Below Covington the Jackson is relatively wide and shallow, and is characterized by alternating riffles and natural pools, with a considerable range of velocities and depths.

The major BOD load to the Jackson River is from a paper mill in Covington owned by the West Virginia Pulp and Paper Company. At times of severe drought flow, essentially all of the flow of the Jackson is withdrawn, used at the paper mill, and then returned to the channel, so that at such times the downstream flow is entirely effluent from the paper mill waste treatment plant. Even after 80 to 90 percent BOD removal in this activated sludge treatment plant, the downstream natural reaeration capacity is not sufficient to prevent serious or complete depletion of the DO resources of the river. Thus, as a further measure to improve the situation, the West Virginia Pulp and Paper Company operates two pairs of mechanical aerators in the river itself at locations below the mill, at times of low stream flow.

Figure 33 is a general map of the Jackson River study locale, showing the river and such features of interest as stream sampling stations, highways, towns, the mill location, and the mechanical aerator locations. Tracer studies of the reaeration capacity of the Jackson between Covington and Clifton Forge, i.e., the critical reach below the paper mill, were performed in July, 1966, by personnel of the FWPCA. Those studies constituted the first field demonstration of the gaseous tracer technique for independently evaluating stream reaeration capacity[9]. During the period immediately prior to the tracer studies, the Jackson was cross-sectioned at intervals of 1,000 feet between Covington and Clifton Forge by staff of the Civil Engineering Department of the Virginia Military Institute. Slopes and water surface elevations were not obtained at that time. In 1970, through the support of the FWPCA, the VMI staff returned to the Jackson River study section to obtain elevations, as by that time the results of the research reported here had clearly indicated that the changes in water surface elevation were important hydraulic data. Rather than level the entire length of the study section from beginning to end, the VMI staff relied upon available bench marks and levelled from those to the 1966 river sampling stations. Some difficulty was encountered in determining the exact locations of some of the earlier stations, especially Station 10, and at some locations the sampling station elevation was obtained by interpolation from elevation measurements at intervening locations. The derived 1966 sampling station elevations were forwarded to the Georgia Tech research staff by Thackston[24], and are presented in Table 14. Immediately prior to the beginning of the 1966 reaeration studies the secondary treatment units at the Westvaco paper mill failed, and the paper mill waste treatment plant operated essentially as a primary plant for several days. The mechanical aerators located downstream in the river were idle at the time, because of the imminent tracer studies. As a result, zero DO's occurred in a reach several miles long immediately below the paper mill.

Dosing Pattern. Table 15 shows the pattern of tracer doses used during the two-week 1966 reaeration study period. Eight separate tracer releases were made at two-day intervals, proceeding systematically downstream from Dunlap Creek, and the releases were designed to provide coverage of each of the subreaches at least twice. The quantities of tracers varied considerably from one release to another, partly because of the inability of the tracer suppliers to provide an accurate assay. The krypton-85 dose therefore ranged from 231 mc to 458 mc, and the tritium dose from 273 mc to 1,108 mc in the individual releases. The average dose used was 335 mc of krypton-85 and 746 mc of tritium. The total amounts released in the eight studies was 2.68 curies of krypton-85 and 5.97 curies of tritium.

Table 14

Jackson River Station Elevations

1966 Sampling Station	Water Surface Elevation Above MSL (1970), ft.
0	1,219.3
1	1,211.1
2	(1,201.8)*
3	(1,187.3)*
4	1,179.9
5	(1,171.1)*
6	(1,163.1)*
7	(1,156.9)*
8	(1,141.4)*
9	(1,132.3)*
10	(1,119.1)*
11	(1,109.0)*
12	(1,093.8)*
13	1,083.2
14	(1,074.0)*
15	1,063.9

---

*Interpolated value

Hydraulic Properties. Typical hydraulic properties of the Jackson River study reaches are summarized in Table 16. The 18-mile study section was divided into 15 subreaches of average length 1.2 miles, from Dunlap Creek in Covington almost to Clifton Forge. Stream flow ranged from 90 cfs at the upper end of the study section to about 130 cfs at the lower end, a moderate drought condition. The cumulative time of flow for the 18-mile study section was about 2.4 days.

As may be seen from Table 16, average subreach velocities ranged from 0.27 to 0.67 ft/sec, and average subreach depths from about 1.7 to 3.1 feet. From Table 14, the total water surface elevation change for the 18-mile study section was about 155 feet. Although the stream was characterized by a

Table 15

Dosing Pattern, Jackson River

Dump Number	Jackson River Sampling Station Number 0	1	2	3	4	5	6	7	8	9	10	11
10	7/11 350 1088											
11	7/13 458 273											
12					7/15 (450) 273							
13					7/17 231 542							
14								7/19 231 554				
15									7/21 321 1088			
16											7/23 318 1042	
17												7/25 321 1108

Key: 7/19-Dump No. 14 released 7/19/66
231 -231 mc of krypton-85 released
554 -554 mc of tritium released

Table 16

Typical Hydraulic Properties

Jackson River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft
10	0-1	90	1.65	4,000	0.673	1.76	134	8.2
10	0-2	90	5.97	10,800	0.503	1.87	179	17.5
10	0-3	90	12.67	19,100	0.419	1.97	215	32.0
10	0-4	93	17.09	26,600	0.432	2.28	215	39.4
10	1-2	90	4.32	6,800	0.437	1.94	206	9.3
10	1-3	90	11.02	15,100	0.381	2.03	236	23.8
10	1-4	94	15.44	22,600	0.407	2.38	231	31.2
10	2-3	90	6.70	8,300	0.344	2.09	262	14.5
10	2-4	96	11.12	15,800	0.395	2.56	243	21.9
10	3-4	96	4.42	7,500	0.471	3.11	204	7.4
12	4-5	102	2.92	6,100	0.580	1.67	176	8.8
12	4-6	102	7.37	11,800	0.445	1.73	229	16.8
12	4-7	102	10.75	15,700	0.406	1.80	251	23.0
12	4-8	104	15.33	23,500	0.426	1.95	244	38.5
12	5-6	102	4.45	5,600	0.350	2.36	292	8.0
12	5-7	102	7.83	9,600	0.341	2.19	299	14.2
12	5-8	105	12.41	17,400	0.389	2.22	269	29.7
12	6-7	102	3.38	3,900	0.321	1.99	318	6.2
12	6-8	106	7.96	11,700	0.408	2.18	260	21.7
14	7-8	108	4.58	7,800	0.473	2.26	228	15.5

Table 16 (continued)
Typical Hydraulic Properties
Jackson River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft
14	7-9	108	9.06	12,200	0.374	2.46	289	24.7
14	7-10	110	11.78	17,600	0.415	2.42	265	(37.8)
14	7-11	110	14.56	22,700	0.433	2.31	254	47.9
15	8-9	108	4.48	4,400	0.273	2.83	296	9.2
15	8-10	111	7.20	9,800	0.378	2.54	294	(22.3)
15	8-11	112	9.98	14,900	0.415	2.33	270	32.4
15	8-12	112	15.03	22,600	0.418	2.37	268	47.6
15	9-10	113	2.72	5,500	0.562	2.30	201	(13.1)
15	9-11	113	5.50	10,500	0.530	2.13	213	23.2
15	9-12	115	10.55	18,300	.482	2.25	239	38.4
16	10-11	113	2.78	5,000	.500	1.95	226	(10.1)
16	10-12	116	7.83	12,800	.454	2.24	255	(25.3)
16	10-13	117	10.48	18,400	.488	2.20	240	(35.9)
16	10-14	117	14.10	23,900	.471	2.17	248	(45.1)
16	11-12	118	5.05	7,800	.429	2.42	275	15.2
16	11-13	122	7.70	13,300	.480	2.30	254	24.8
16	11-14	124	11.32	18,800	.461	2.23	269	35.0
17	11-15	125	15.05	25,000	.461	2.08	271	45.1
17	12-13	128	2.65	5,600	.587	2.13	218	10.6
17	12-14	128	6.27	11,000	.487	2.10	263	19.8
17	12-15	129	10.00	17,200	.478	1.94	270	29.9
17	13-14	128	3.62	5,500	.422	2.06	303	9.2

Table 16 (continued)
Typical Hydraulic Properties
Jackson River

Dump	Reach	Flow cfs	Time of Travel hrs	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft
17	13-15	129	7.35	11,600	.438	1.85	294	19.3
17	14-15	130	3.73	6,100	.454	1.66	286	10.1

considerable range of velocities and depths at the individual 1000-ft cross-sections (depths from 0.6 to 5.3 feet), no remarkable hydraulic features such as waterfalls, shoals or violent rapids occurred.

Reaeration Coefficients. All of the reaeration rate coefficients obtained during the 1966 studies of the Jackson River are provided in Table 17. As may be seen, 80 observations of the reaeration rate coefficients were obtained. The range of these coefficients was from about 0.07/hr to 0.39/hr at 25°C. Subreach 9-10 was unusual compared to the rest of the stream, in that it included a relatively long shallow riffle section, and was characterized by an associated unusually high reaeration capacity. However, the observed mean value of K_{ox} (0.36/hr at 25°C) did not compare with the values observed in the Flint or South at features such as falls, Panola Shoals or the violent rapids sections in those streams.

Reference to Table 17 shows that the reproducibility of the test results was very good. As noted earlier, the degree of pollution of the Jackson River during these studies was unusually high, due to failure of the secondary treatment units at the paper mill. As a result, it is probable that the values of K_{ox} reported in Table 17 are lower than would have been found otherwise, especially in the reaches immediately below the paper mill. Specifically, the observed results for Dumps 10 and 11 are probably quite a bit lower than usual, perhaps by 20 to 30 percent, due to that unusual pollution situation.

Figures 34 and 35 are a graphical presentation of all of the results for the Jackson River studies. The numerical values of K_{kr} shown on the graphs refer to the prevailing river temperatures and flows at the time of the individual tracer releases. The values of K_{ox} shown in Table 17 have been obtained by use of the $K_{kr}:K_{ox}$ ratio of 0.83 and the temperature coefficient of 1.022/°C.

Referring to Figure 34 for the upper study reaches, the generally parallel nature of the lines is evident, and indicates a considerable degree of hydraulic uniformity. This becomes more evident by reference to Table 17, after correction of the data to a common temperature. From Table 17, for the entire upper study section (Stations 0 to 8) the range of observed values of K_{ox} at 25°C was from 0.07 to 0.21 per hour. Of the 41 reported values of K_{ox}, 35 fall within the range 0.10 to 0.15 per hour, and the median result of 0.12 per hour for K_{ox} at 25°C represents a reasonably good single value for the entire upper study section.

Table 17

Observed Reaeration Coefficients, Jackson River

Reach	K_{ox} per hour @ 25°C								
	10	11	12	13	14	15	16	17	Mean
0-1	0.146	0.134	-	-	-	-	-	-	0.140
0-2	0.119	0.139	-	-	-	-	-	-	0.129
0-3	0.120	0.117	-	-	-	-	-	-	0.119
0-4	0.108	0.104	-	-	-	-	-	-	0.106
1-2	0.108	0.104	-	-	-	-	-	-	0.124
1-3	0.115	0.114	-	-	-	-	-	-	0.115
1-4	0.104	0.100	-	-	-	-	-	-	0.102
2-3	0.120	0.094	-	-	-	-	-	-	0.107
2-4	0.102	0.081	-	-	-	-	-	-	0.092
3-4	0.076	0.064	-	-	-	-	-	-	0.070
4-5	-	-	0.153	0.208	-	-	-	-	0.181
4-6	-	-	0.116	0.141	-	-	-	-	0.129
4-7	-	-	0.122	0.141	-	-	-	-	0.132
4-8	-	-	0.125	0.134	-	-	-	-	0.130
5-6	-	-	0.093	0.097	-	-	-	-	0.095
5-7	-	-	0.111	0.115	-	-	-	-	0.113
5-8	-	-	0.119	0.118	-	-	-	-	0.119
6-7	-	-	0.134	0.139	-	-	-	-	0.137
6-8	-	-	0.133	0.128	-	-	-	-	0.131
7-8	-	-	0.132	0.122	0.128	-	-	-	0.127
7-9	-	-	-	-	0.133	-	-	-	-
7-10	-	-	-	-	0.181	-	-	-	-

Table 17 (continued)

Observed Reaeration Coefficients, Jackson River

Reach	K_{ox} per hour @ 25°C								
	10	11	12	13	14	15	16	17	Mean
7-11	-	-	-	-	0.174	-	-	-	-
8-9	-	-	-	-	0.138	0.137	-	-	0.137
8-10	-	-	-	-	0.217	0.238	-	-	0.228
8-11	-	-	-	-	0.197	0.202	-	-	0.200
8-12	-	-	-	-	-	0.181	-	-	-
9-10	-	-	-	-	0.343	0.385	-	-	0.364
9-11	-	-	-	-	0.244	0.248	-	-	0.246
9-12	-	-	-	-	-	0.197	-	-	-
10-11	-	-	-	-	0.146	0.120	0.140	-	0.135
10-12	-	-	-	-	-	0.136	0.148	-	0.142
10-13	-	-	-	-	-	-	0.184	-	-
10-14	-	-	-	-	-	-	0.169	-	-
11-12	-	-	-	-	-	0.144	0.152	0.184	0.160
11-13	-	-	-	-	-	-	0.198	0.195	0.197
11-14	-	-	-	-	-	-	0.174	0.191	0.183
11-15	-	-	-	-	-	-	-	0.168	-
12-13	-	-	-	-	-	-	0.283	0.213	0.248
12-14	-	-	-	-	-	-	0.192	0.196	0.194
12-15	-	-	-	-	-	-	-	0.161	-
13-14	-	-	-	-	-	-	0.125	0.181	0.153
13-15	-	-	-	-	-	-	-	0.140	-
14-15	-	-	-	-	-	-	-	0.102	-

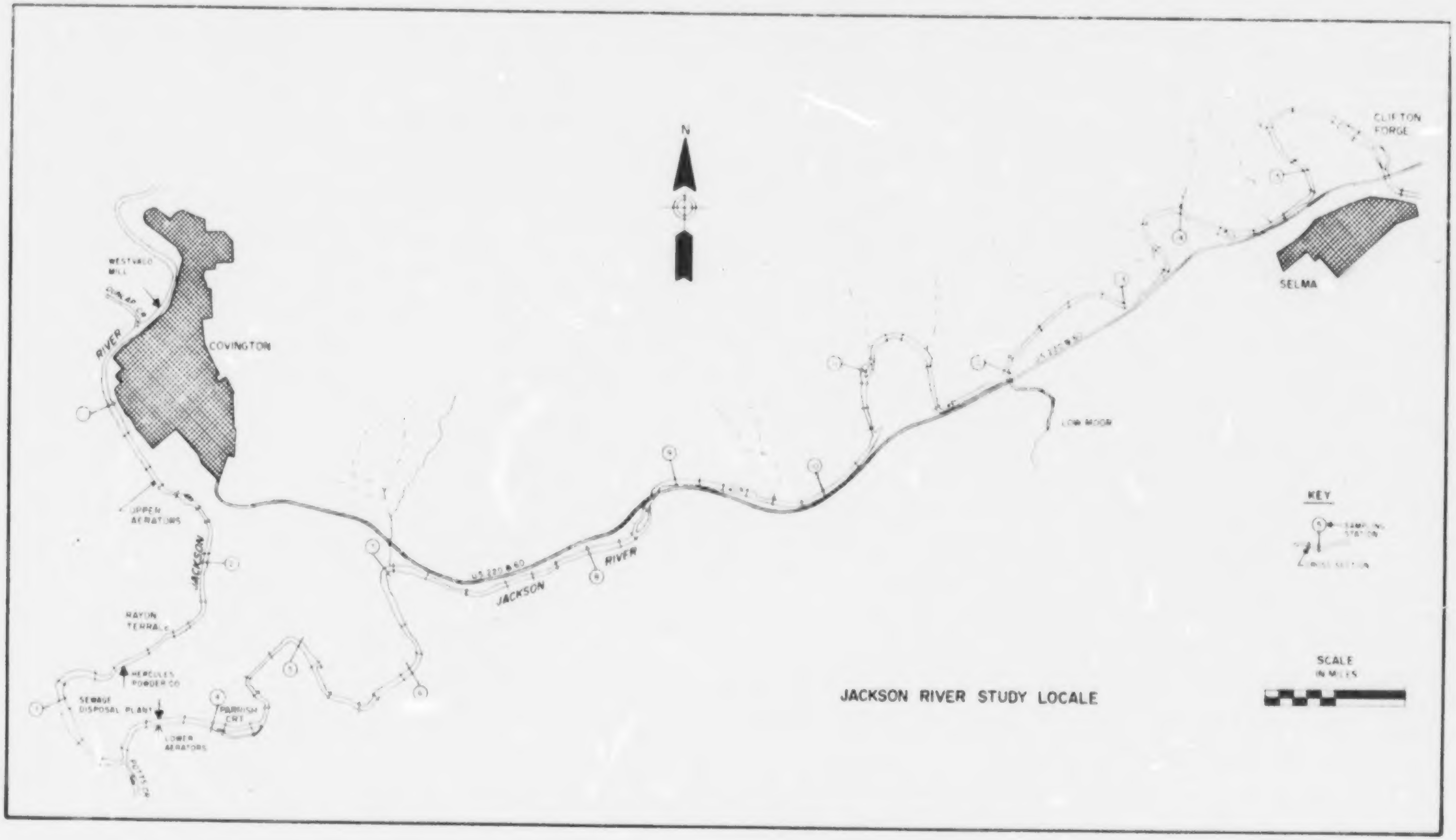

N
WESTVACO MILL
DUNLAP CR.
RIVER
COVINGTON
UPPER AERATORS
JACKSON
RAYON TERRACE
HERCULES POWDER CO
SEWAGE DISPOSAL PLANT
PARRISH CRT
LOWER AERATORS
POTTS CR
US 220 & 60
JACKSON
RIVER
LOW MOOR
CLIFTON FORGE
SELMA
KEY
SAMPLING STATION
CROSS SECTION
SCALE IN MILES
JACKSON RIVER STUDY LOCALE

FIGURE 33

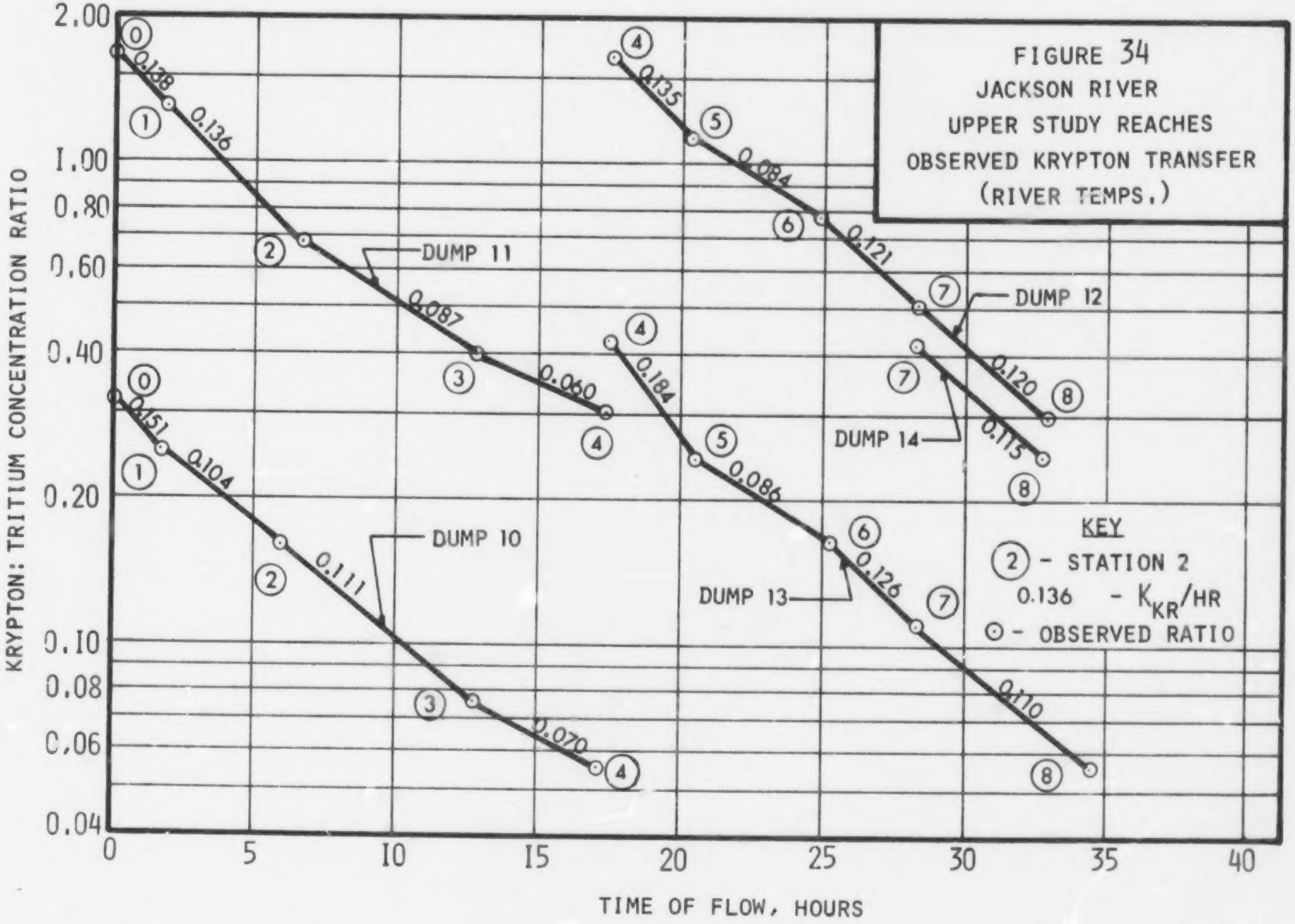


FIGURE 34
JACKSON RIVER
UPPER STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

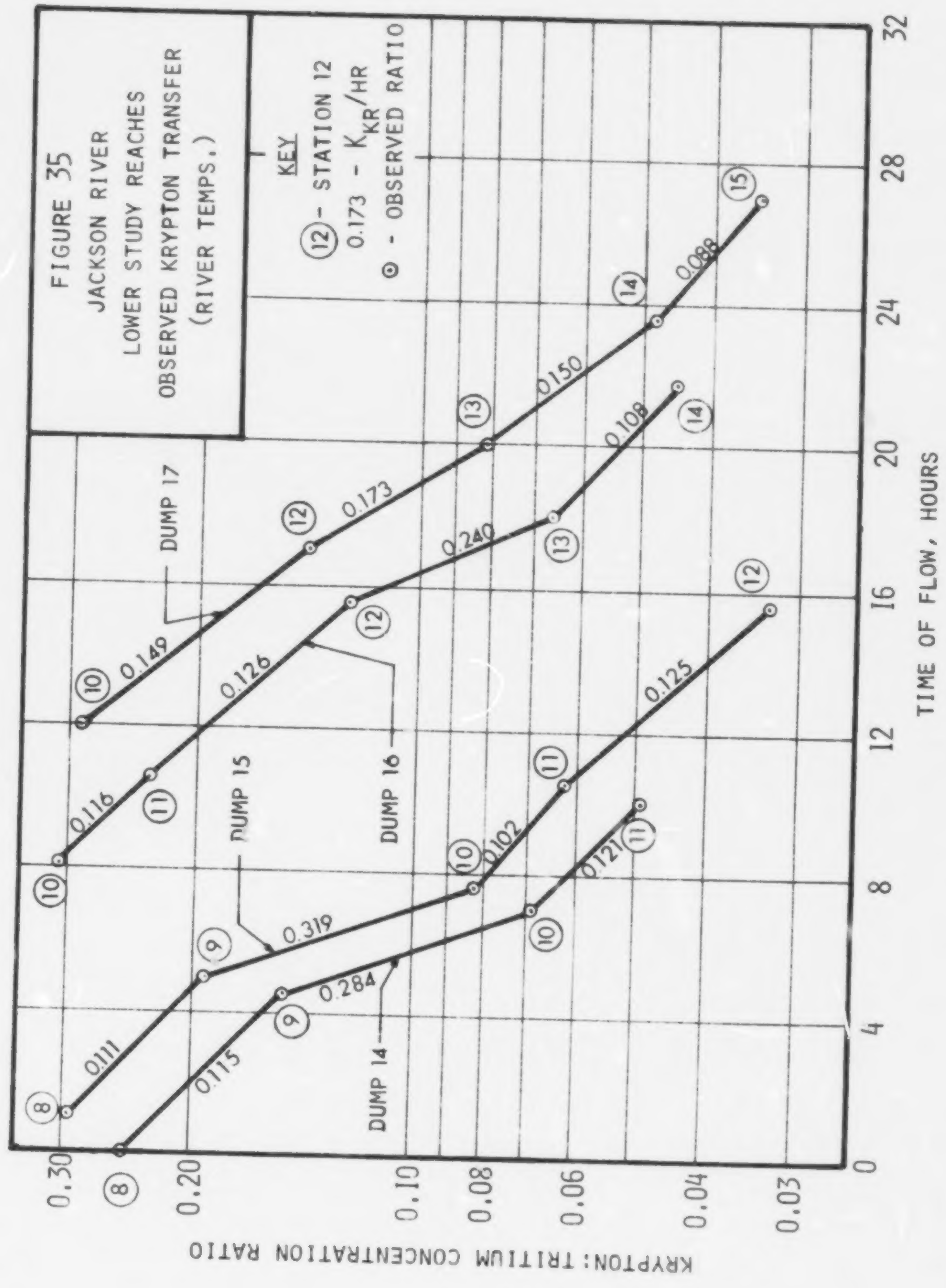


FIGURE 35
JACKSON RIVER
LOWER STUDY REACHES
OBSERVED KRYPTON TRANSFER
(RIVER TEMPS.)

Figure 35, which depicts the observed results for the lower study section (Stations 8 to 15), shows somewhat more variability from one subreach to another. The subreach 9-10 in particular is clearly different from the others covered by Dumps 14 and 15, as noted above, and was characterized by higher values of K_{OX} (see Table 17).

CHATTAHOOCHEE RIVER

The Chattahoochee is one of the principal rivers of the southeast. It rises in the mountains of northeast Georgia and flows south and west some 436 miles to the Florida line, where it joins the Flint River to form the Apalachicola. The Chattahoochee drains approximately 1,450 square miles of mountain and piedmont country above Atlanta. It is the principal source of public water supply for the Atlanta metropolitan area, where such withdrawals totalled 130 to 140 mgd in 1966.

About 45 miles upstream from Atlanta, the Chattahoochee is impounded in Lake Sidney Lanier by Buford Dam, constructed in the 1950's by the Corps of Engineers. Lake Lanier is a multiple purpose reservoir, important for flood control, hydroelectric power and low flow augmentation, as well as recreation. The river flow from Buford Dam is reregulated at Morgan Falls Dam, about 10 miles upstream from Atlanta. Morgan Falls Dam is owned and operated by the Georgia Power Company, and a minimum release of 750 cfs is maintained at all times.

The Chattahoochee falls rather sharply (as much as five feet per mile) from Morgan Falls to a location near the beginning of the reaeration tracer study section. From there, the fall is more gradual for some 120 miles until the stream reaches the Fall Line, where it again drops rather abruptly before flattening out on its way to the Gulf of Mexico.

Figure 36 is a general map showing most of the Chattahoochee River study locale. The main reaeration tracer study section, about 18.5 miles in length, extended from Station 0 at Georgia Highway 280 to Station 6 (not shown), located almost two miles downstream from the Georgia Highway 92 bridge (Station 5). The main source of pollution, the Clayton STP, is located almost a mile above Station 0: during the reaeration tracer study period, this plant operated as a primary treatment plant, with frequent bypassing of raw sewage. In addition, two steam generating plants, (Plants Atkinson and McDonough), located between the Clayton STP and Station 0, use Chattahoochee River water for cooling, and thus raise the temperature of the downstream Chattahoochee. Additional

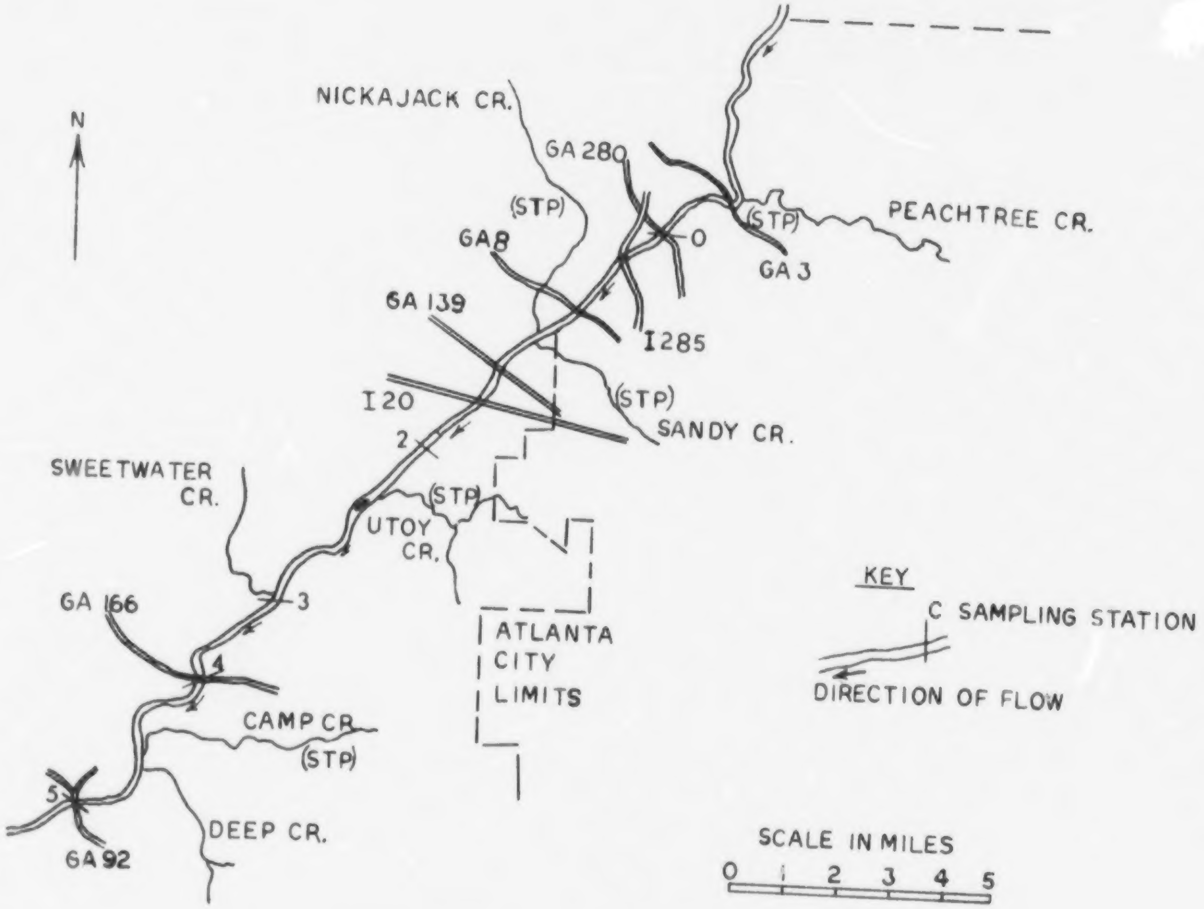

N
NICKAJACK CR.
GA 280
(STP)
PEACHTREE CR.
(STP)
GA 3
0
GA8
GA 139
I285
(STP)
SANDY CR.
I20
2
SWEETWATER CR.
(STP)
UTOY CR.
3
GA 166
4
ATLANTA CITY LIMITS
CAMP CR.
(STP)
5
DEEP CR.
GA92
KEY
C SAMPLING STATION
DIRECTION OF FLOW
SCALE IN MILES
0 1 2 3 4 5

FIGURE 36
CHATTAHOOCHEE RIVER LOCALE

pollution entered the main Chattahoochee via the several tributaries (Nickajack Creek, Sandy Creek, Utoy Creek, Sweetwater Creek, Camp Creek). During the work week, as a result, the Chattahoochee was heavily polluted, and at locations in the upper portion of the reaeration tracer study section the predominantly mud and sand bottom was the residence of tremendous populations of redworms.

With the exception of Dump XXV, all of the reaeration tracer studies were performed on Sundays, at quite low, steady flow. The Chattahoochee is used for power production during the work week, and the flow in the vicinity of Atlanta therefore undergoes a sharp fluctuation during each day. With the cooperation of the Georgia Power Company and the Corps of Engineers, it was possible to schedule steady critical low flows on Sundays for reaeration study purposes, without undue interference with power production. However, as will be seen in this and subsequent sections of this report, this necessary Sunday tracer study schedule also meant quite low river BOD's, due to characteristically low weekend pollution loads. Also, companion studies of the effect of pollution on the reaeration capacity of the Chattahoochee demonstrated a sharply different condition during the usual work week. Hence, the reaeration capacities observed during these tracer studies represent a pollution condition more of the future than the present, when pollution of the Chattahoochee in the vicinity of Atlanta will be considerably reduced.

Tracer Dump XXV, the last study, was conducted at a substantially higher flow than the earlier studies, in order to obtain some information at other flows. As in the earlier studies, a steady flow for this tracer study was arranged with the cooperation of the Georgia Power Company.

Dosing Pattern. Table 18 shows the dosing pattern that was used in the tracer studies of the reaeration capacity of the Chattahoochee River. Dose XVIII (not shown, and not reported further) was similar to Dose XVII and followed it by three weeks; difficulties associated with the dose assay, together with unusual and ineffective location of river sampling stations, resulted in observed reaeration capacities that were both questionnable and not comparable to the results obtained at regular sampling points from the other tracer releases. Accordingly, the results from Dose XVIII are not reported here.

As indicated in Table 18, a total of nine separate tracer studies was conducted, beginning in the fall of 1969 and extending to the fall of 1970. The Chattahoochee River studies were begun in the fall of 1969, immediately after completion of the Flint and South River studies, with the intention of

Table 18

Dosing Pattern, Chattahoochee River

Dump Number	Chattahoochee River Sampling Station Number 0	2	3	4	5	6
XVI	10/12/69 2,600 4,000					
XVII		10/19/69 1,330 4,000				
XIX	7/26/70 4,480 5,000					
XX	8/2/70 5,250 5,000					
XXI			8/16/70 2,220 5,000			
XXII			8/30/70 3,610 5,000			
XXIII		9/13/70 3,980 5,000				
XXIV			9/20/70 2,410 5,000			
XXV	11/24/70 5,930 10,000					

Key: 7/26/70-Dump XIX released on 7/26/70 - Station 0
4,480 - 4,480 mc of krypton-85 released
5,000 - 5,000 mc of tritium released.

completing most if not all of the field research by late 1969 or early 1970. However, it proved to be impractical to continue the Chattahoochee studies into late November and December because of considerably colder water temperatures and frequent rainfall. Thus, following Dose XVII, the remainder of the field operations were rescheduled for the summer of 1970.

As with the studies in the Flint and South Rivers, the quantities of tracer varied from one release to another, largely due to the inability of the supplier to deliver the quantity of dissolved krypton-85 ordered. Thus, the amount of krypton-85 actually released ranged from as little as 1,330 mc to as much as 5,250 mc in the series of doses at critical low flow, whereas the tritium dose was as ordered and ranged from 4,000 to 5,000 mc. For Dose XXV, at higher flow, the krypton-85 dose was 5,930 mc and the tritium dose 10,000 mc, as requested from the supplier. A total of 31.8 curies of krypton-85 were released in the nine studies, and a total of 48 curies of tritium. The average dose at critical low flow (Doses XVI - XXIV) was 3,240 mc of dissolved krypton-85 and 4,750 mc of tritium.

Hydraulic Properties. The Chattahoochee River is characterized by a high degree of hydraulic uniformity in the reaeration study section. In contrast to the Flint and South, the Chattahoochee below the Georgia Highway 280 bridge has long straight sections of relatively uniform width and depth, often with high, steep banks that prevent ready access. Table 19 shows typical hydraulic properties of the Chattahoochee associated with the flows prevailing during the reaeration tracer studies.

Referring to Table 19, at the critical low river flow of about 1,100 cfs in the tracer study section, the stream depth, velocity and cross-sectional area were each quite uniform: the mean depth of about 4.0 feet did not vary appreciably from reach to reach, or, for that matter, within any reach; the mean velocity averaged about 1.8 ft/sec, and the mean cross-sectional area about 600 sq ft. At the higher flow associated with Dump XXV (3,300 cfs), the mean velocity was higher, about 2.5 ft/sec, the mean depth increased to about 7.6 ft, and the cross-sectional area about doubled. No detailed cross-sectional measurements were made below the Georgia Highway 92 bridge (Station 5), hence typical depths and cross-sectional areas are not shown in Table 19 for the reach 5-6. The bottom character of the study section was predominantly mud and sand, with occasional short more rocky areas.

Table 19
Typical Hydraulic Properties
Chattahoochee River

Dump	Reach	Flow cfs	Time of Travel hrs.	Length ft	Velocity ft/sec	Depth ft	X-sect Area sq ft	WS Elev Change ft
XIX	0-2	1,076	4.93	31,500	1.77	4.16	608	6.7
	0-3	1,076	8.73	54,000	1.72	4.16	625	10.5
XXIII	2-3	1,030	3.27	22,500	1.91	4.02	540	3.8
	2-4	1,130	5.39	35,000	1.80	3.84	627	6.6
	2-5	1,130	9.45	57,500	1.69	3.89	668	9.5
XXIV	3-4	1,180	1.70	12,500	2.04	3.62	579	3.8
	3-5	1,180	5.19	35,000	1.87	3.90	630	5.6
	3-6	1,180	7.34	44,000	1.67	-	-	6.8
XXIV	4-5	1,180	3.49	22,500	1.79	4.06	660	2.9
	4-6	1,180	5.64	31,500	1.55	-	-	4.2
XXIV	5-6	1,180	2.15	(9,000)*	(1.16)*	-	-	1.2
XXV	0-4	3,300	7.53	66,500	2.45	7.65	1,350	13.3
	0-5	3,300	10.08	89,000	2.45	7.66	1,350	17.8

---

*Estimated value.

Because of the high steep banks and the general inaccessibility of the Chattahoochee, it was not feasible for the levelling party to establish a continuous series of reference elevations directly along the banks of the river. Instead, it was necessary to level along more circuitous routes, tie into reference elevations and bench marks established earlier by others, and thereby establish tapedown location elevations for each river sampling point. Thus, it was not possible to conduct a single, continuous elevation survey from Station 0 to Station 6, checking against established bench marks along the way, as was done in the Flint and South River studies. The procedure used for the Chattahoochee elevation study thus depended, for accuracy, more heavily than usual on the accuracy of the elevations reported for established bench marks. The Georgia Tech research party elevation surveys were tied into or checked against bench marks established by or for the U. S. Army Corps of Engineers, the Georgia Highway Department, the U. S. Geological Survey, Six Flags over Georgia, the Georgia Power Company and the Atlanta Water Works. Unfortunately, the results indicate clearly that all of the available bench marks are not equally valid, and the discrepancies were discovered too late to permit the additional surveys necessary to resolve conflicts among established bench mark elevations.

Figure 37 shows the water surface elevation profile that has been developed for the reaeration tracer study section of the Chattahoochee River, for the steady critical low flow associated with Dumps XVI through XXIV. The elevations for the individual sampling stations were finally established by a procedure of cross-checking relevant level notes, tapedowns made during the tracer studies and all available bench mark elevations. The resulting water surface profile is thus believed accurate. However, some doubt must remain, as it proved impossible to resolve all bench mark elevation conflicts. It is to be hoped that in the future some authority such as the City of Atlanta will undertake a thorough survey designed to firmly establish the elevations of existing and new bench marks, and to resolve present conflicts.

Reaeration Coefficients. Table 20 provides a summary of all of the reaeration coefficients observed in the Chattahoochee River studies of 1969-70. The total of nine separate releases, as detailed in Table 18, yielded 37 observed values of the reaeration rate coefficient. Of these, 31 observed values (Dumps XVI through XXIV) are associated with the critical low flow of about 1,100 cfs in the tracer study reach, and 6 observations of K_{OX} (Dump XXV) reflect a flow of about 3,300 cfs. Of the 31 observed values at low flow,

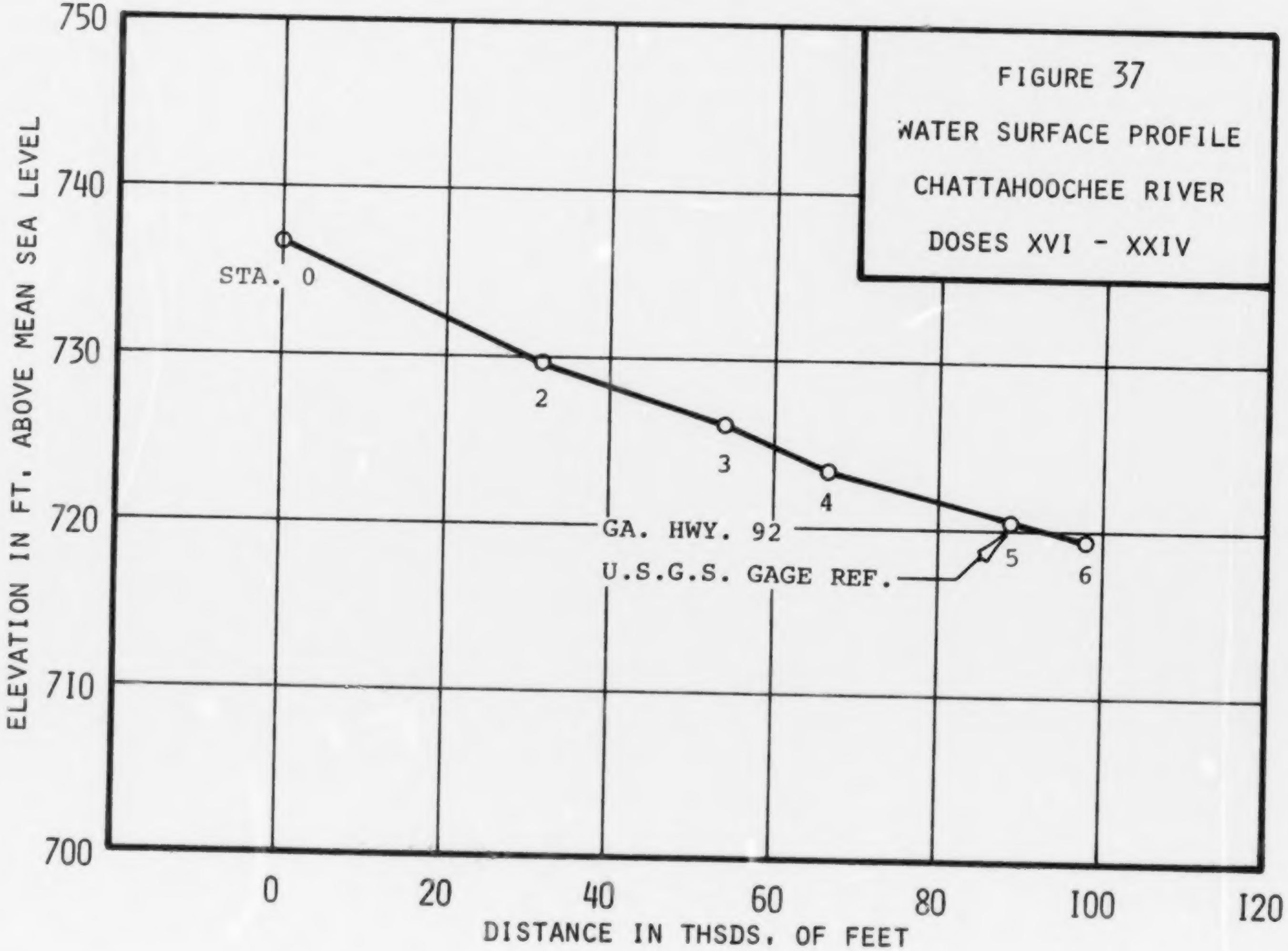


FIGURE 37
WATER SURFACE PROFILE
CHATTAHOOCHEE RIVER
DOSES XVI - XXIV

Table 20

Observed Reaeration Coefficients, Chattahoochee River

Reach	K_{ox} per hour @ 25°C									
	XVI	XVII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	MEAN
0-2	0.077	-	0.100	0.036	-	-	-	-	0.030	0.061
0-3	-	-	0.077	0.036	-	-	-	-	-	0.052
0-4	-	-	-	-	-	-	-	-	0.040	-
0-5	-	-	-	-	-	-	-	-	0.042	-
2-3	-	0.070	0.049	0.012	-	-	0.040	-	-	0.043
2-4	-	0.042	-	-	-	-	0.057	-	0.049	0.049
2-5	-	-	-	-	-	-	0.045	-	0.047	0.046
3-4	-	(-0.005)	-	-	(0.081)	(0.002)	(0.084)	(0.049)	-	0.043
3-5	-	-	-	-	0.044	0.026	0.048	0.040	-	0.040
3-6	-	-	-	-	-	0.019	-	0.038	-	0.029
4-5	-	-	-	-	0.026	0.039	0.029	0.035	0.045	0.035
4-6	-	-	-	-	-	0.025	-	0.034	-	0.030
5-6	-	-	-	-	-	(0.005)	-	(0.033)	-	(0.019)

---

*Parenthetical values questionnable.

four were obtained in the 1969 study period and the remainder during the summer and fall of 1970. The prevailing river water temperatures ranged from 20°C to 28°C for Dumps XVI through XXIV, whereas the prevailing river water temperature for Dump XXV, at 3,300 cfs, was 10°C. The detailed data for each tracer release are provided in Appendix IV.

As noted earlier, all of the tracer releases associated with the critical low flow of 1,100 cfs occurred on Sundays, and pollution loads were quite low. The significance of this situation and of other related studies of pollutant effects on the reaeration capacity will be discussed further below.

Referring to Table 20, the reproducibility of observed results was quite good in some reaches (e.g., reaches 2-4, 2-5, 3-5, 4-5) and poorer in others (e.g., reach 3-4, 5-6). The individual observed results for the reaches 3-4 and 5-6 are all contained within parentheses in Table 20, to indicate that they are considered more questionnable than the other results. Those reaches were relatively short compared to the others, both in distance and time of flow, and therefore generally characterized by less gas loss and somewhat larger relative error. In the case of the reach 3-4, a sufficient number of observations of K_{OX} was made (n=5) to yield a good mean value for that reach; in the case of reach 5-6, only two observations of K_{OX} were made, one of which (K_{OX} = 0.005 per hour) was undoubtedly poor. Hence, the mean value of K_{OX} for the reach 5-6 is also indicated as questionnable in Table 20, by the use of parentheses.

That the reproducibility of individual observed results is generally somewhat poorer for the Chattahoochee River studies than for others is not surprising in terms of the test conditions. Although the tracer doses were the largest used in any of the studies reported here, the river flow was also much larger, and the tracer doses were actually the smallest used on a mc/cfs basis. In addition, average velocities (and dispersion) were considerably greater in the Chattahoochee than in the other streams, and reaeration capacity (and actual tracer gas losses) considerably smaller. The net result of this combination of factors was a somewhat lower degree of reproducibility of results.

To compensate, the Chattahoochee studies were designed so as to provide more than the usual two observations of K_{OX} per basic study reach, so that good estimates of the mean value of K_{OX} could be derived for each basic reach. Specifically, for the reaches 0-2 and 2-3, four separate values of K_{OX} were obtained; for the reaches 3-4 and 4-5, five separate values of K_{OX} were obtained in each case. As may be seen from Table 20, this degree of repetition of field testing provided a highly consistent set of mean values of K_{ox} for the whole study section 0-5.

Referring to Table 20, for the basic study reaches 0-2, 2-3, 3-4 and 4-5, the mean value of K_{ox} at 25°C ranged from 0.035 to 0.061 per hour, and tended to decrease proceeding downstream. The mean of all 37 observed values of K_{ox} was 0.042 per hour at 25°C; neglecting those reaches that include station 6 (the reach 5-6 was covered only twice), the mean of the 31 values of K_{ox} that were observed for the study section 0-5 was 0.045 per hour at 25°C.

It should be noted also that the observed values of K_{ox} for Dump XXV (at 3,300 cfs) were completely consistent among themselves and also were fully consistent with the results obtained for the other tracer studies conducted at a low flow of 1,100 cfs. Thus, an increase in river flow by 300 percent, and an associated near-doubling of stream depth, made no difference in the prevailing value of K_{ox}. This phenomenon was also observed clearly in connection with the Flint River studies discussed earlier (Dump III vs. Dump XIV), as well as in connection with the fluctuating flows in the Patuxent and South River studies. In brief, in all such cases observed, changes in river flow by a factor of two or three did not result in any observable significant change in the reaeration coefficient, K_{ox}, which remained constant within relatively narrow limits.

The mean value of K_{ox} of 0.045 per hour at 25°C (k_{ox}, to the base 10 = 0.47 per day at 25°C) thus constitutes a highly accurate basic reaeration coefficient for the Chattahoochee River immediately below the Clayton STP outfall and Plants Atkinson and McDonough of the Georgia Power Company, for a distance of about 17 miles (main study reach 0-5), for associated steady flows of 1,100 to 3,300 cfs within that section of the river. It is emphasized, however, that no studies were performed during periods of the rapidly fluctuating flows associated with power peaking. Also, river BOD's were generally quite low, representative of future rather than present weekday pollution levels.

Figure 38 is the usual semilog plot of results for the Chattahoochee River tracer studies. The observed krypton: tritium ratios have been plotted vs. time of flow for each tracer release. These data reflect river water temperatures at the time of each study, as provided in Appendix IV, and have not been corrected to a common temperature. The associated values of K_{kr} at prevailing river temperatures are shown. As noted above, the individual results for the short reaches 3-4 and 5-6 are regarded as more questionnable, and hence those lines are shown as dashed rather than full lines.

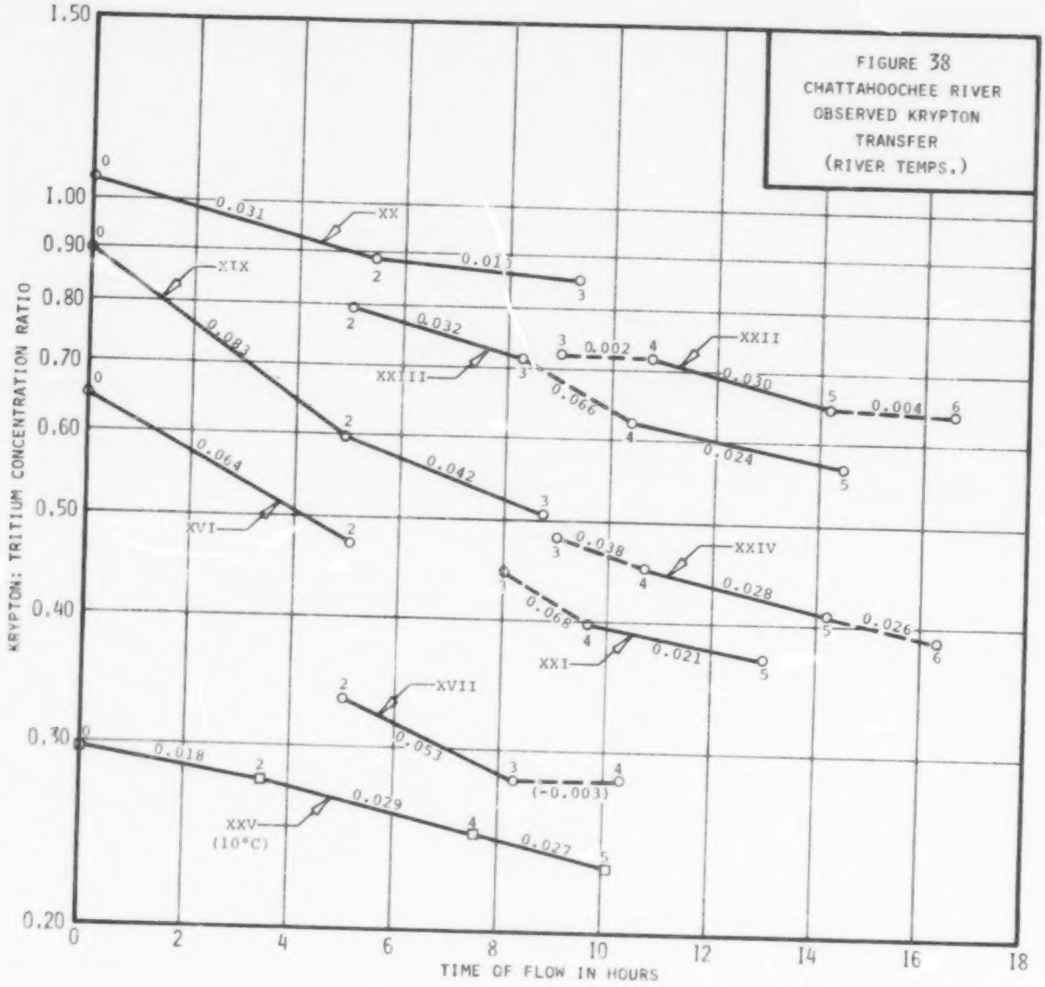


FIGURE 38
CHATTAHOOCHEE RIVER
OBSERVED KRYPTON
TRANSFER
(RIVER TEMPS.)

In connection with Dump XXV, it should be recalled that the prevailing water temperature was only 10°C, as compared to temperatures ranging from 20°C to 28°C for the other studies; also, XXV was at a considerably higher river flow, as evidenced by the shorter times of flow.

The generally parallel trend of results is evident in Figure 38, allowing for the individual departures noted above. Converted to values of K_{ox} at a common temperature, as provided in Table 20, the results are quite consistent.

BOD Results. BOD time series were run as a matter of routine for all of the Chattahoochee River reaeration tracer studies. In each case, large BOD samples were collected at each tracer sampling station and a BOD time series developed for each such sample. Samples were also taken for such analysis at the Atlanta Water Works, well above the Clayton STP outfall. The time series results are not reproduced here, as that degree of detail is not relevant. However, the 5-day BOD's are indicative of the general level of pollution in the study reach at various times, and are discussed briefly below.

The BOD's associated with the 1969 Sunday tracer studies were relatively high compared to results observed during the 1970 studies. Specifically, the 5-day, 20°C Sunday BOD ranged from 8.0 to 11.4 mg/l in the reach 0-2 during Dump XVI, and from 6.7 to 10.7 mg/l in the reach 0-3 during Dump XVII. The BOD was still somewhat high for a Sunday during Dump XIX, the first of the 1970 series, ranging from 4.5 to 9.2 mg/l in the reach 0-3. However, beginning with Dump XX, on 8/2/70, the 5-day, 20°C, Sunday BOD dropped to new low levels and remained low. For example, in the reach 0-3 the observed BOD's ranged from 3.2 to 4.2 mg/l for Dump XX. In the succeeding tracer studies, with four stations represented in each case, the maximum 5-day BOD's observed were 4.0, 3.4, 4.5, 3.4 and 3.4 mg/l, respectively, for Dumps XXI through XXV. The reduction observed in 1970 coincided well with improved waste control measures reported by the Georgia Water Quality Board.

The Sunday BOD's observed and noted above are not indicative of usual weekday pollution levels, but are quite low in comparison. In addition, as noted earlier, the steady low flows arranged for the Sunday tracer studies, are in no way representative of the rapidly changing weekday flow situation in the Chattahoochee below Atlanta. Under these circumstances, detailed oxygen balance studies for the tracer study section, using the observed reaeration coefficients, have not been deemed profitable so far as the purposes of this research are concerned, and have not been performed.

Pollutant Effects. Although the research studies of the effects of pollution on stream reaeration capacity have generally been deferred for separate discussion in Section VII, some comment regarding the Chattahoochee studies is desirable here. In brief, as shown in Section VII, a number of Chattahoochee River water samples were tested for pollutant effect. Sunday samples taken during the course of Dumps XIX through XXIII showed no pollutant effect--that is, the K_{kr}(or, the K_{ox}) was not reduced because of the presence of pollution added to the river below the Atlanta Water Works. In contrast, weekday samples showed a definite reduction due to such pollution. Specifically, those tests showed that during the week K_{kr} (and K_{ox}) might be expected to be only perhaps 80 percent of the magnitude that would occur in the unpolluted condition. Hence, the 25°C K_{ox} of 0.045 per hour observed for the reach 0-5 during these studies should be reduced to about 0.036 per hour if it is to be used for oxygen balance studies under weekday conditions at similar flows.

Section VII

EXPERIMENTAL RESULTS - LABORATORY STUDIES

This section of the report includes a summary of the observed results of a series of laboratory investigations dealing with the effects of pollutants on the reaeration coefficient, K_{ox}. The main purpose of these studies was to develop and demonstrate a laboratory test procedure for evaluating the effects of a variety of pollutants on the gas transfer or reaeration capacity. Although it is suspected that certain pollutants may also affect the dissolved oxygen saturation limit, C_s, these studies did not include an investigation of that possibility.

Various investigators have reported that detergent surface active agents (surfactants) reduce the rate of gas transfer, the reduction being dependent on the concentration and the hydrodynamic conditions of turbulence and mixing. In order to study the effect of detergent surfactants on gas transfer, a series of tests was conducted using various concentrations of the detergent surfactant linear alkylate sulfonate (LAS) in distilled water.

At the time of the laboratory studies, there was also considerable public attention being devoted to the detergent "builder" nitrilotriacetic acid (NTA) as a substitute for high phosphate detergents. Due to this interest, laboratory tests were conducted for the purpose of evaluating the possible effects of pure NTA on reaeration in turbulent water.

The effect of oil on gas transfer in turbulent water was considered to be of sufficient interest to warrant a separate series of tests with various concentrations of reagent grade mineral oil in distilled water.

The field reaeration measurements reported in Section VI of this report were often obtained in highly polluted stream reaches. As the polluted river waters contain numerous contaminants, some of which may effect the reaeration capacity, laboratory tests were conducted on actual river water samples for the purpose of evaluating the effects of mixed pollutants on the reaeration of natural waters.

The experimental results reported in the following portions of this Section of the report are given in terms of the krypton transfer coefficient, K_{kr}, for convenience and consistency, as the principal focus of interest was on the nature and extent of effect rather than upon a particular gas. The reported results can be converted to values of K_{ox}, if that is desired, by use of the 0.83 conversion. All of the tests reported here were conducted at a constant temperature of 20°C.

POLLUTANT EFFECTS - PURE SUBSTANCES

All of the tests of pollutant effects were conducted in the laboratory reactor system described in Section V of this report (see Figure 19). In brief, one test of the effect of a pollutant consisted of two reactor runs: the first was conducted on clean water and provided a value of K_{kr} referred to here as K_{clean} as a baseline evaluation of the hydrodynamic conditions; the second run was conducted under the same hydrodynamic conditions as the first, with the pollutant added, providing a comparable value of K_{kr} referred to here as $K_{polluted}$. In keeping with the current practice of referring to pollutant effects in terms of an "alpha" factor, the value of $K_{polluted}$ divided by K_{clean} is denoted here as "alpha". For further details of the experiment, the reader is referred to Section V.

LAS Tests. Figure 39 is a semilog plot of the krypton:tritium concentration ratios vs. elapsed time for two typical reactor tests with LAS. The two distilled water runs (no LAS present), 13A and 19A, had K_{kr} values of 2.07/hr and 2.04/hr, respectively. The test water for run 13B contained 1.0 mg/l of LAS and the water for run 19B contained 8.3 mg/l of LAS. The observed values of K_{kr} for runs 13B and 19B were 1.91/hr and 1.40/hr, respectively. The resulting "alpha" factor for test 13 was

$$\alpha = \frac{1.91}{2.07} = 0.92$$

and for test 19

$$\alpha = \frac{1.40}{2.04} = 0.69$$

A total of eighteen separate tests were conducted using distilled water with LAS concentrations ranging from 1.0 to 11.8 mg/l. Twelve of the 18 tests were conducted at essentially the same stirrer speed, or the same rate of mixing and surface replacement. The other six tests were conducted at different stirrer speeds but with constant LAS concentration.

Table 21 summarizes the results obtained in the 12 constant mixing tests. If mixing had been truly identical in each of the 12 tests, the numerical value of K_{kr} would have been the same for all 12 runs with distilled water only, that is, for all of the runs designated as Run A. As may be seen from

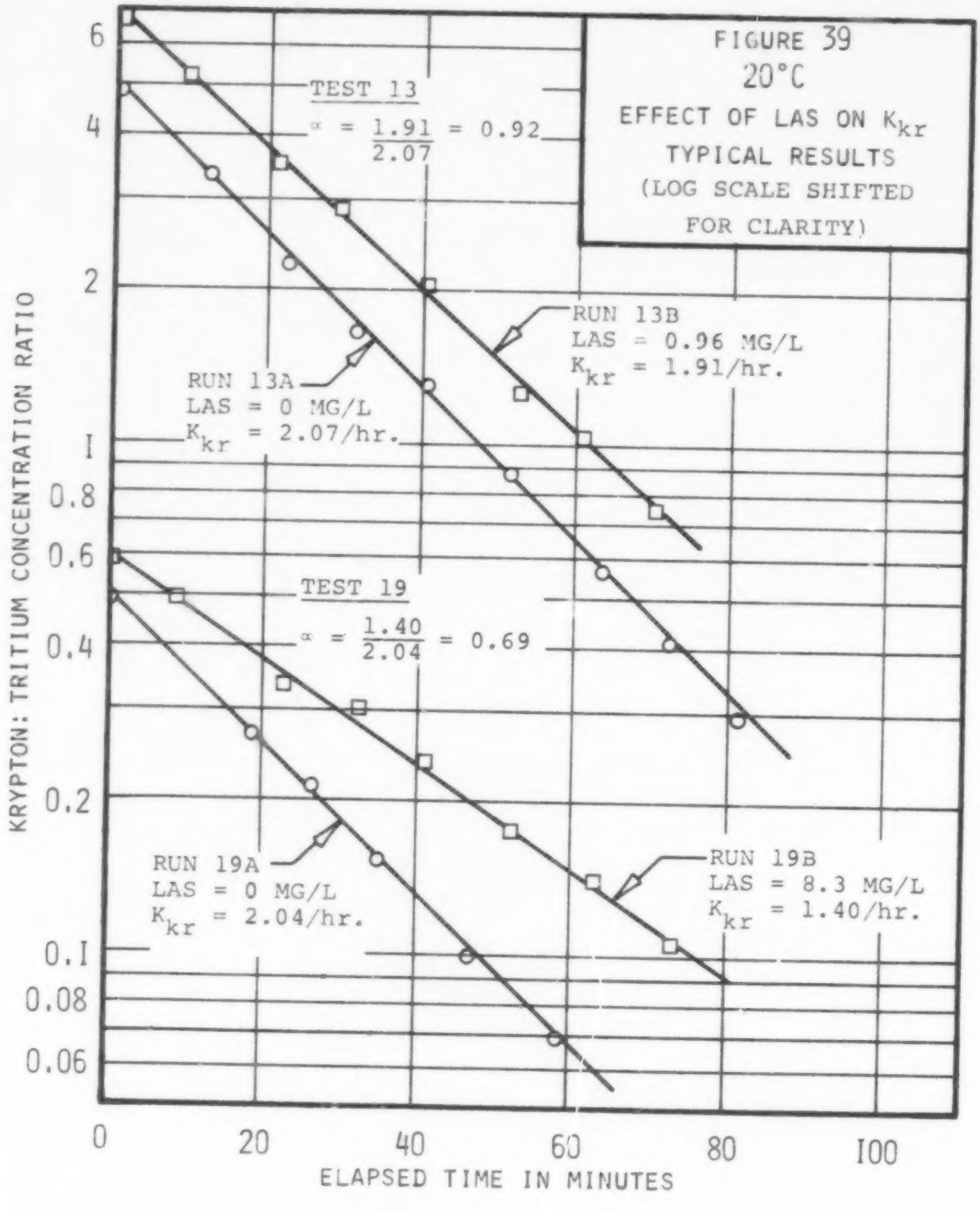


FIGURE 39
20°C
EFFECT OF LAS ON K_{kr}
TYPICAL RESULTS
(LOG SCALE SHIFTED FOR CLARITY)

Table 21

Reactor Tests with LAS

(Constant Mixing)

Test Number	Run	LAS Conc. mg/l	K_{kr}/hr (20°C)		"alpha"
			Water	Water + LAS	
8	A	0.0	1.79		
	B	3.0		1.43	0.80
9	A	0.0	1.95		
	B	3.8		1.44	0.74
10	A	0.0	1.81		
	B	4.8		1.37	0.76
11	A	0.0	1.90		
	B	6.0		1.29	0.68
12	A	0.0	1.90		
	B	11.0		1.24	0.65
13	A	0.0	2.07		
	B	1.0		1.91	0.92
14	A	0.0	2.13		
	B	2.0		1.83	0.86
15	A	0.0	2.03		
	B	5.2		1.58	0.78
16	A	0.0	2.13		
	B	7.0		1.56	0.73
17	A	0.0	1.90		
	B	9.2		1.43	0.75
18	A	0.0	2.02		
	B	9.5		1.41	0.70
19	A	0.0	2.04		
	B	8.3		1.40	0.69

the data presented in Table 21, the Run A values of K_{Kr} for the 12 tests ranged from 1.79/hr to 2.13/hr, and the average value was 1.97/hr. All 12 of the Run A values were within 10 percent of the mean for these tests.

Figure 40 is a plot of the results obtained at the essentially constant mixing speed, the observed values of K_{Kr} for the LAS + Water runs (Run B data) being plotted against LAS concentration. As may be seen, these results appear to plot as two separate groups. The main group, for tests 12 through 19, describe a good straight line over the range of observation, the value of K_{Kr} diminishing as the LAS concentration is increased. The first four tests, 8 through 11, plot as a separate group, the results being considerably lower but adequately fitted with a parallel line (shown as a dashed line in Figure 40). The reason for this discrepancy cannot be stated with certainty. Undoubtedly, between tests 11 and 12 some change in experimental procedure occurred, possibly an improved procedure for cleaning the reactor between runs or an improvement in the analytical method for LAS. All of the test runs yielded very good straight line fits of the krypton:tritium concentration ratios on semilog paper. Whatever the cause of the discrepancy in runs 8B through 11B the results of the entire series of tests with LAS are clear: as the concentration of LAS increases, there is increased effect on the gas transfer coefficient, and the relationship involved appears to be linear for the range of observation indicated in Figure 40. The line through the main group of data, Runs 12B through 19B, passes through $K_{Kr} = 1.97$/hr at a concentration of zero LAS, and that is the experimentally observed value for distilled water alone, hence the other lower group of data must be regarded as erroneous in the sense noted above.

Figure 41 is a plot of the data of Table 21 according to the usual practice of referring to such effects in terms of the "alpha" factor. In this case, the "alpha" factors provided in Table 21 have been plotted against LAS concentration. As may be seen, the"alpha" factor becomes smaller as LAS concentration increases, indicating greater reduction of K_{Kr}. The smooth curve has been fitted to the data of Figure 41 by eye, and the data appear to extrapolate back to an "alpha" of about 1.0 at zero LAS concentration.

Table 22 summarized the results of the six reactor tests (12 runs) that were conducted with distilled water in which the LAS concentration was kept essentially constant while the rate of mixing was varied. The LAS concentrations ranged from 9.8 to 11.8 mg/l of LAS, with an average of 10.4 mg/l. The value of K_{Kr} for distilled water only (Runs designated A) is indicative of the actual degree of mixing or surface water replacement, and varied from 0.078/hr to

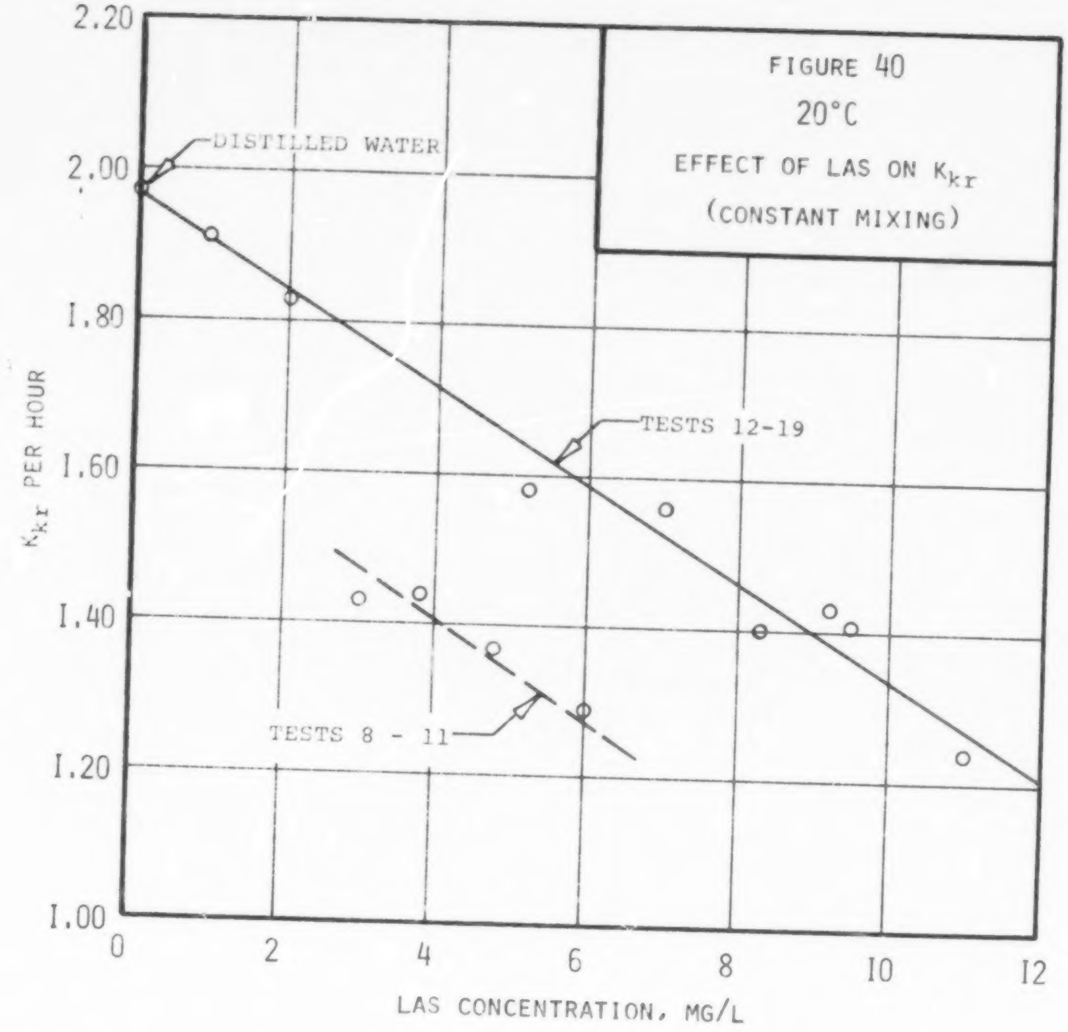


FIGURE 40

20°C

EFFECT OF LAS ON K_{kr}

(CONSTANT MIXING)

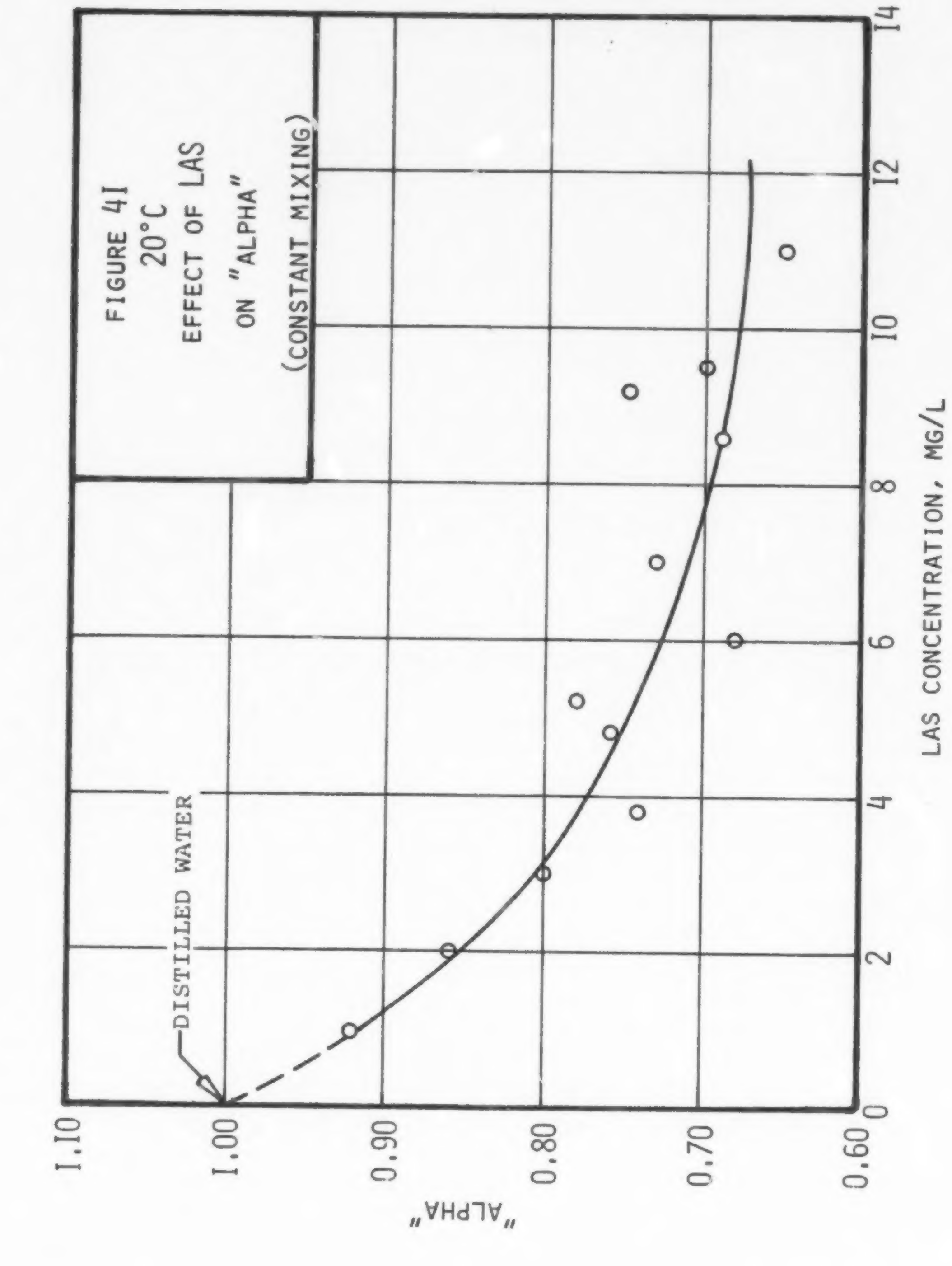


FIGURE 41
20°C
EFFECT OF LAS
ON "ALPHA"
(CONSTANT MIXING)

4.67/hr.

Table 22

Reactor Tests with LAS

(Constant LAS Concentration)

Test Number	Run	LAS Conc. mg/l	K_{kr}/hr (20°C)		
			Water	Water + LAS	"alpha"
21	A	0.0	4.67		
	B	9.8		2.68	0.57
22	A	0.0	0.439		
	B	10.0		0.417	0.95
23	A	0.0	0.078		
	B	11.8		0.075	0.96
24	A	0.0	3.58		
	B	10.3		2.11	0.59
25	A	0.0	0.180		
	B	10.7		0.171	0.95
26	A	0.0	0.895		
	B	10.0		0.640	0.72

The results of the tests with constant concentration of LAS are clear from the data provided in Table 22. If the data are arrayed in order of increasing value of K_{kr} for distilled water, it will be seen that the "alpha" factor decreases accordingly. Thus, at a constant concentration of LAS, the greater the degree of turbulent mixing, the greater the corresponding reduction of gas transfer, or the less the gas transfer coefficient. As shown in Section VI, in streams like the Flint and the South Rivers, much of the action of reaeration takes place in short distances associated with rapids, shoals and waterfalls. It is at just such hydraulic features that the damaging effect of detergents will be at a maximum, in terms of reducing the magnitude of K_{ox}.

The reactor tests with LAS have thus provided important insight into the nature and extent of effects on reaeration capacity of surfactants like LAS and the household detergents that contain such surfactants. In brief, not only does LAS or like material reduce the gas transfer and reaeration capacity, but this damaging effect of detergents on stream reaeration capacity is twofold - the resulting reduction in K_{kr} or K_{ox} increases as the detergent concentration increases, and for any one concentration this reduction is at its greatest at hydraulic features such as rapids, shoals and falls, where reaeration might otherwise be expected to be at a most beneficial maximum. For example, four samples collected from the South River during the field tracer study period contained from 1.8 to 2.7 mg/l of LAS - according to the results provided in Table 21 and Figure 41, a reduction of K_{ox} to perhaps 85 percent of the clean water value would be expected over Panola Shoals, where a great deal of reaeration takes place.

NTA Tests. Four separate tests of distilled water with NTA added were conducted, for the purpose of obtaining an initial evaluation of its effect on gas transfer and reaeration. The NTA concentrations in these tests ranged from 7.5 to 16.1 mg/l. The results are tabulated in Table 23.

Table 23

Reactor Tests with NTA

Test		NTA Conc.	K_{kr}/hr (20°C)		
Number	Run	mg/l	Water	Water + NTA	"alpha"
27	A	0.0	0.462		
	B	7.8		0.438	0.95
28	A	0.0	0.499		
	B	16.1		0.475	0.95
29	A	0.0	0.194		
	B	7.5		0.182	0.94
30	A	0.0	0.477		
	B	7.8		0.477	1.11

The results provided in Table 23 indicate clearly that pure NTA had no significant effect on the gas transfer capacity in the range of concentrations and mixing rates tested. The average "alpha" result was 0.99.

Mineral Oil Tests. A total of thirteen separate tests were conducted with mineral oil in distilled water, the mineral oil concentrations ranging from 16 to 458 mg/l. Eleven of these tests were conducted at essentially the same mixing rate with variable concentration of oil, while four of the tests were conducted at one concentration but variable mixing rate. Although such tests with laboratory grade mineral oil and distilled water cannot be extrapolated directly to field situations, the tests have provided very interesting insight into the nature and effects of mineral oil (and presumably other oils) on gas transfer in turbulent water systems.

Table 24 provides the results obtained from all thirteen tests with mineral oil. The first eleven tests, Test 31 through 41, were at essentially one mixing rate, as indicated by the observed values of K_{kr} in distilled water only (no oil). Referring to the Run A data for those tests, the values of K_{kr} ranged from 0.78/hr to 0.98/hr, with a mean of 0.90/hr. Figure 42 is a semilog plot of the Krypton: tritium concentration ratios for two typical reactor tests with mineral oil. The two distilled water runs, 36A and 40A, were characterized by K_{kr} values of 0.97/hr and 0.98/hr, respectively (see Figure 42). Run 36B contained 360 mg/l of mineral oil, and an associated K_{kr} of 1.99/hr was observed, whereas Run 40B contained only 16 mg/l of mineral oil and had an associated K_{kr} of 1.14/hr. The "alpha" factors were 2.05 for Test 36, and 1.17 for Test 40. As may be seen from Figure 42, the observed data describe excellent straight lines on the semilog plots, and the individual derived vlaues of K_{kr} contain very little possibility of error.

It is evident from the results presented in Table 24 and Figure 42 that the presence of mineral oil enhances the gas transfer capacity of turbulent water, an effect opposite to that observed for the surfactant LAS.

Figure 43 shows the effect of mineral oil on the magnitude of K_{kr} at a constant rate of mixing. The values of K_{kr} have been plotted against the oil concentration, in mg/l, for Tests 31 through 41. The trend of results is clear - the magnitude of K_{kr} increases sharply with increasing concentration of oil, an effect opposite to that observed with LAS. The relationship appears to be curvilinear rather than straight. As shown in Figure 43, one result (Test 38) appears to be quite doubtful, for reasons not known. Actually, reference to the results in Table 24 and to Figure 43 indicates that the four results for the sequence of Tests 37 through 40 are all somewhat high on a relative basis. Regardless of the reason for such scatter, in no case did the presence of mineral oil fail to increase the magnitude of K_{kr}. As shown in Figure 43, the trend of results is also through the observed mean value for distilled water (no oil) at zero oil concentration.

Figure 44 is a plot of the "alpha" factor vs. mineral oil concentration at essentially constant stirrer speed (Tests 31 through 41). In no case was an "alpha" of less than 1.00 observed; in every case the K_{kr} for Run B (water + oil) was greater than the comparable K_{kr} for Run A. Referring to Figure 44, the trend of observed results is quite clear, there being only one observation (Test 38) that is

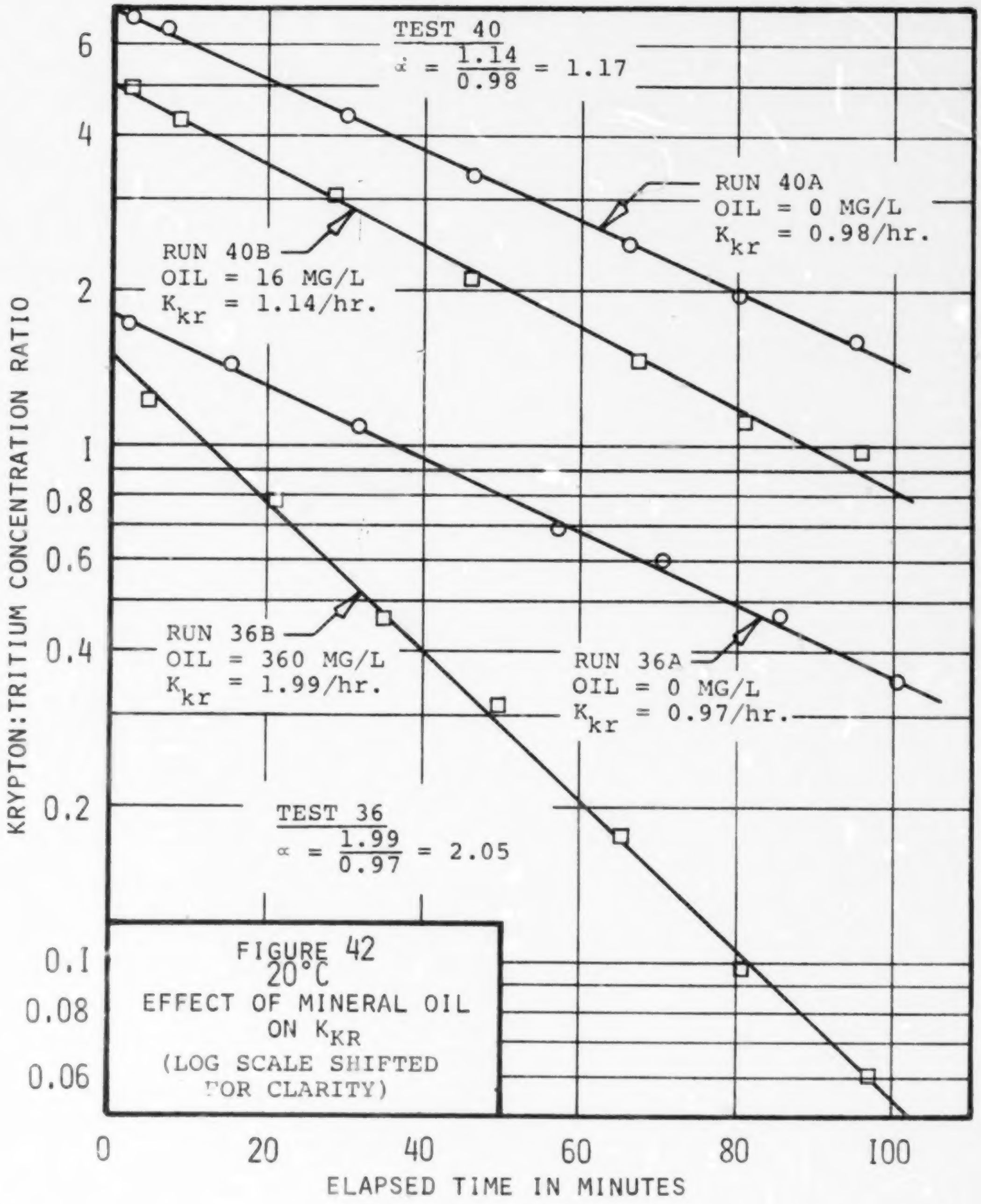


FIGURE 42
20°C
EFFECT OF MINERAL OIL
ON K_{KR}
(LOG SCALE SHIFTED
FOR CLARITY)

Table 24

Reactor Tests with Mineral Oil

Test Number	Run	Oil Conc. mg/l	K_{kr}/hr (20°C) Water	K_{kr}/hr (20°C) Water + Oil	"alpha"
31	A	0	0.894		
	B	230		1.73	1.94
32	A	0	0.866		
	B	458		2.03	2.34
33	A	0	0.789		
	B	230		1.70	1.87
34	A	0	0.849		
	B	121		1.36	1.60
35	A	0	0.780		
	B	45		1.09	1.40
36	A	0	0.970		
	B	360		1.99	2.05
37	A	0	0.904		
	B	17		1.19	1.32
38	A	0	0.914		
	B	41		1.73	1.89
39	A	0	0.956		
	B	42		1.41	1.47
40	A	0	0.978		
	B	16		1.14	1.17
41	A	0	0.945		
	B	123		1.46	1.54
42	A	0	5.01		
	B	230		5.01	1.00
43	A	0	1.43		
	B	230		2.01	1.41

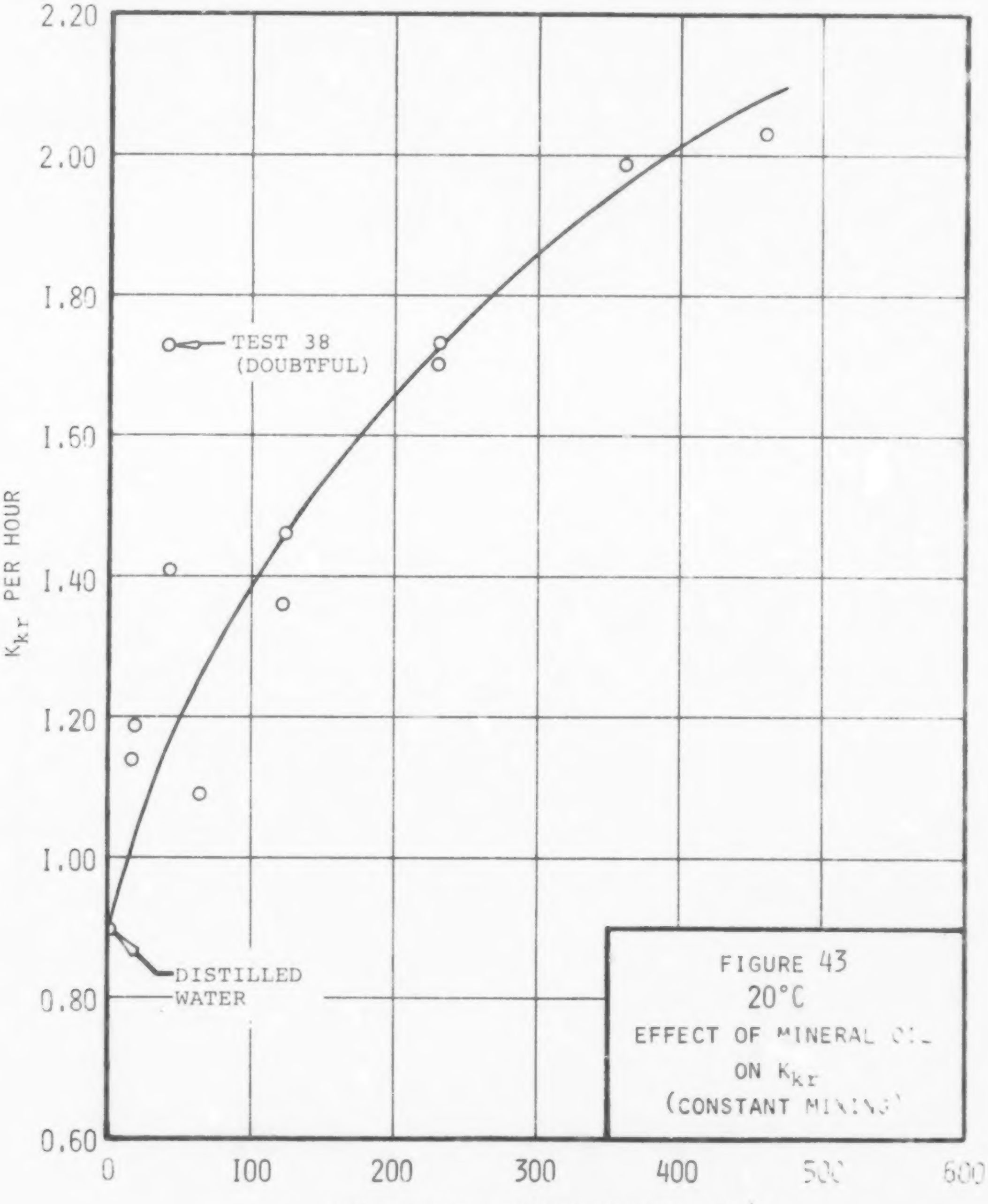


FIGURE 43
20°C
EFFECT OF MINERAL OIL
ON K_{kr}
(CONSTANT MIXING)

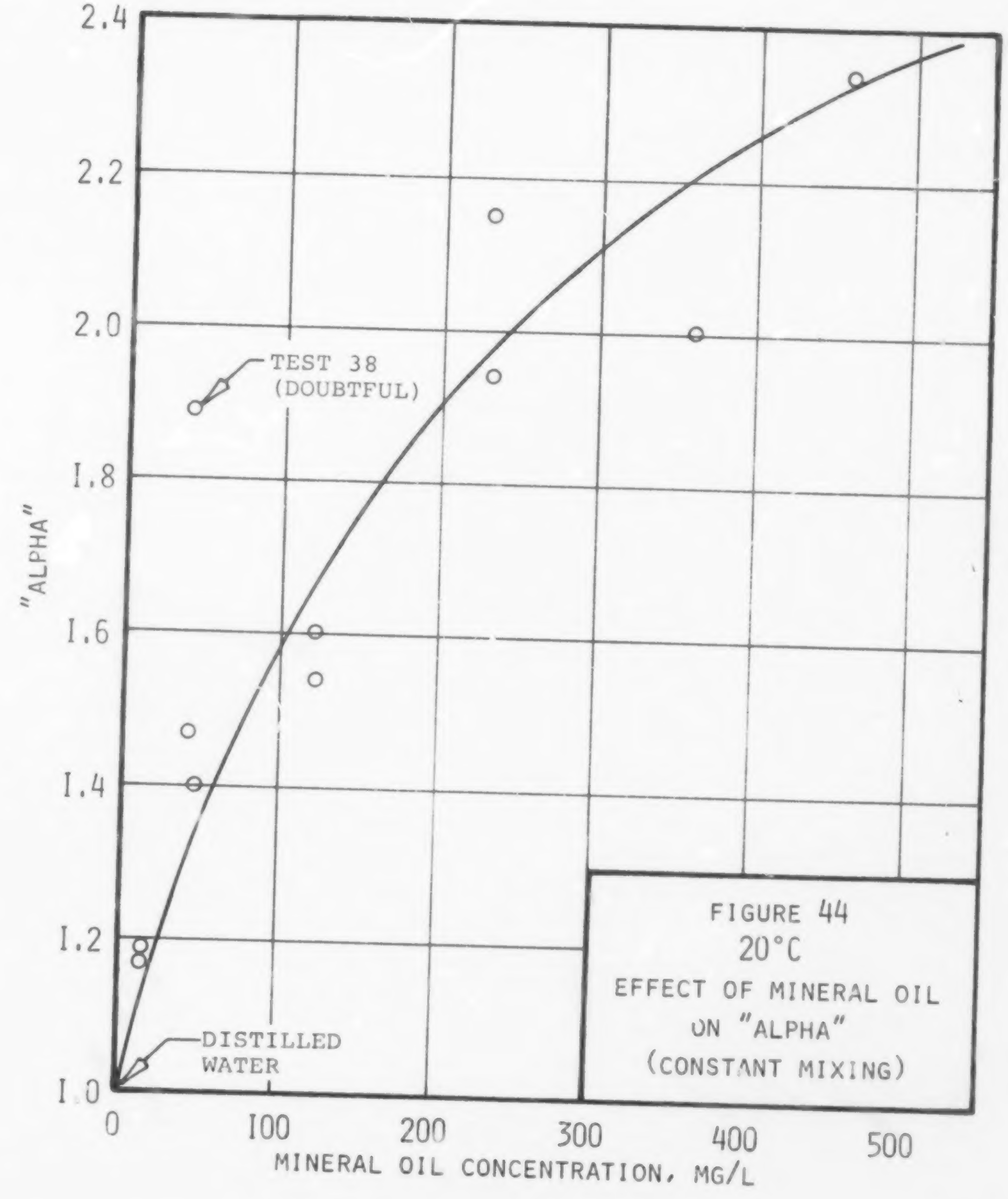


FIGURE 44
20°C
EFFECT OF MINERAL OIL
ON "ALPHA"
(CONSTANT MIXING)

clearly not compatible with the other results. Even in that case, the observed value of "alpha" is too large, rather than too small, indicating too great a value of K_{kr} for Run B. The reason for this odd result in Test 38 is not apparent from careful review of the test data, and cannot be stated here.

Referring again to Table 24, four of the total of thirteen tests were conducted at the same concentration of mineral oil (230 mg/l) but at different stirrer speeds, as evidenced by the results for K_{kr} with distilled water only. Those four tests were Numbers 31, 33, 42, and 43. There are not sufficient data for plotting and curve-sketching, but again the results of the tests are quite clear. In brief, it is evident that, for constant concentration of mineral oil, the value of "alpha" diminishes as the rate of mixing is increased, and at relatively high rates of mixing (see Test 42) the mineral oil was found to have no effect on K_{kr} ("alpha" = 1.00). In contrast, at the lowest rates of mixing (Tests 31 and 33) the highest values of "alpha" were observed. Again, these observed results show an effect just opposite to that observed earlier in the experiments with LAS - in that case, the greater the turbulent mixing, the greater the effect of LAS on K_{kr} and K_{ox}.

The fundamental reasons for the foregoing observed effects of mineral oil (and, for that matter, LAS) have not been explained by these experiments. In all of the experiments with mineral oil, the degree of turbulent mixing was sufficiently great to keep the oil apparently uniformly distributed throughout the test volume of water, at least to the extent that this could be observed visually. No oil film was ever observable at the water surface. Of course, the concentrations of oil were relatively large as a rule, but even at the lowest concentrations, 16 or 17 mg/l, there was a definite enhancement of gas transfer in the presence of the oil. One can speculate as to the reasons for this observation. For example, it would appear possible that the oil altered the quality of the test water in the sense of making less difficult the escape of the krypton gas molecules at the water surface. Alternatively, it appears quite possible that the oil acted in some way as a lubricant, modifying the surface tension of the water or increasing the rate of surface water replacement, especially at the walls of the vessel, in such a fashion as to facilitate gas transfer. Neither these nor other speculations can be demonstrated or tested with the available results. However, the clear demonstration of the opposing nature of the effects of mineral oil and LAS emphasizes the importance of further research designed to examine more closely the basic reasons for such effects on the gas transfer capacity of turbulent water systems.

POLLUTANT EFFECTS - RIVER WATERS

A total of fifteen separate pollutant effects tests were conducted with water samples taken from the South and Chattahoochee Rivers in the vicinity of Atlanta. The purposes of these tests were to demonstrate the test procedure with natural river water samples and to obtain some estimate of the actual effects on reaeration capacity of treated or partially treated wastes routinely released to these streams

Weekday Tests. Ten of the tests of pollutant effect on stream reaeration capacity were conducted on samples collected from the streams during the usual work week (Monday through Friday), when pollution loads are relatively high. Table 25 provides a summary of those test results, and also includes one other set of results for a test (Number 44) comparing distilled water with clean Chattahoochee River water collected at the City of Atlanta Water Works intake. The comparison of distilled water against clean Chattahoochee River water indicated no significant difference (See Test 44 - "alpha" = 1.05) in gas transfer capacity. In tests 45 through 49, Chattahoochee River water taken at Station 0 (See Section VI) was compared to clean river water from the water works intake location. In each case the gas transfer capacity for the polluted river water was lower than that for the clean upstream river water, the "alpha" values ranging between 0.60 and 0.88. Although the number of tests was not sufficient for firm conclusions regarding the effect of the mixing rate, the results appear to indicate a decreasing "alpha" factor associated with an increase in the rate of mixing, as noted earlier in connection with the pure LAS studies.

Tests 53 and 54 compared polluted Chattahoochee River water against distilled water. The river water samples were collected only about 1,000 feet below the Clayton STP outfall, in order to obtain samples with the highest degree of pollution, and to more definitely ascertain the source of pollution causing the reduction in gas transfer capacity. The Run B "alpha" values of 0.80 and 0.83 at two different mixing speeds indicated definitely that the Clayton STP effluent was responsible for the reduction in gas transfer capacity found in the earlier tests (Test Numbers 45 through 49) of Station 0 river samples.

Tests 50, 51 and 52 compared pollutant effects in the South River against distilled water, as no really unpolluted

Table 25

Reaeration Effects of Pollution Loads in Streams

(Weekday Samples)

		Sample					
		Clean	Polluted		K_{kr}/hr(20°C)		
Test Number	Run	Distilled or Water Works	River	Station*	Clean	Polluted	"alpha"
44	A	Dist.			2.23		
	B	WW	Chatt	-		2.35	1.05
45	A	WW			2.35		
	B		Chatt	0		1.48	0.63
46	A	WW			2.47		
	B		Chatt	0		1.48	0.60
47	A	WW			0.520		
	B		Chatt	0		0.404	0.78
48	A	WW			1.92		
	B		Chatt	0		1.17	0.61
49	A	WW			0.49		
	B		Chatt	0		0.43	0.88
50	A	Dist.			0.937		
	B		South	G		0.796	0.85
51	A	Dist.			0.830		
	B		South	A		0.680	0.82
52	A	Dist.			1.04		
	B		South	J		0.74	0.71
53	A	Dist.			0.830		
	B		Chatt	**		0.690	0.83
54	A	Dist.			2.04		
	B		Chatt	**		1.63	0.80

---

* See Section VI for Station locations.

** About 1,000 ft below Clayton STP outfall.

location was available as a source of clean test water. Referring to Table 25, the polluted sampling station locations are the same as those referred to in Section VI, and the observed "alpha" values ranged from 0.71 to 0.85. The mean "alpha" value was 0.79 at an average mixing rate associated with a K_{kr} for distilled water of 0.94/hr. The South is heavily polluted at the locations sampled, and is known to have LAS concentrations of 2 mg/l or more at times. Reference to the effects of LAS on gas transfer (see Table 22, especially) indicates that LAS was probably not the only pollutant involved in reducing the gas transfer capacity of the South River water.

Sunday Samples. All of the Chattahoochee River field tracer studies of reaeration capacity were conducted on Sundays, because that was the only day of the week when steady low river flows could be obtained (the Chattahoochee is used for power production, and has a highly variable flow during other days of the week). Thus, the river was not as highly polluted during the tracer studies, compared to usual weekday periods. Accordingly, a series of five tests was conducted with river water collected on Sundays during the field tracer studies. The results of those pollutant effects tests are provided in Table 26. Referring to Table 26, the field study numbers and the station identification numbers are those referred to in Section VI, and all polluted test results were compared to clean water samples taken at the City of Atlanta Water Works intake (see Runs designated A in Table 26).

Table 26

Reaeration Effects of Pollution Loads in Streams

(Sunday Samples)

Field Study	Test Number	Run	Station	K_{kr}/hr (20°C) Clean	Polluted	"alpha"
XIX	55	A	WW	0.445		
		B	3		0.419	0.94
XX	56	A	WW	0.107		
		B	2		0.131	1.22
XXI	57	A	WW	0.458		
		B	4		0.470	1.03
XXII	58	A	WW	0.446		
		B	4		0.430	0.96
XXIII	59	A	WW	0.431		
		B	3		0.452	1.05

Referring to the results given in Table 26, the observed values of "alpha" ranged from 0.94 to 1.22, with an average of 1.04. Test Number 56 was somewhat different - it was conducted at a considerably lower rate of mixing (K_{kr} for Run A = 0.107/hr vs. about 0.44/hr for the other four tests), in an effort to achieve a degree of turbulence more nearly approaching that of the river itself. As may be seen, at that low mixing rate it appears that it was more difficult to reproduce the same mixing condition in the test system, and a high "alpha" value of 1.22 resulted. Neglecting the result for Test 56, the observed "alpha" values at essentially constant mixing speed ranged only from 0.94 to 1.05, and averaged 1.00. These test results indicated clearly that on Sundays the reaeration capacity of the Chattahoochee River was not significantly affected by the presence of pollution. Thus, the reaeration capacities reported earlier in Section VI of this report probably reflect the pollution situation of the future (when the Clayton STP has been upgraded to secondary treatment and there is no bypass of untreated sewage) rather than the present weekday polluted condition.

SECTION VIII

HYDRAULIC PROPERTIES RELATED TO REAERATION

This section of the report contains an introductory discussion regarding the traditional concepts of the relationships between stream hydraulic properties and reaeration capacity, together with a critique based upon the theory presented earlier (Section IV). This introductory review is followed by comparisons of the observed reaeration coefficients with those predicted by the various available predictive models, together with appropriate comment. Finally, a new approach is presented, in which an energy dissipation model for stream reaeration is developed from simple theoretical considerations and the resulting models for gas transfer and reaeration are tested with the results obtained from the field tracer studies.

INTRODUCTORY DISCUSSION

It was noted as early as 1911 by Black and Phelps[1] that stream reaeration is directly related to the rate of turbulent mixing, and almost 50 years ago Streeter and Phelps[2] reasoned that their newly defined reaeration rate coefficient, K_2, could be related to stream turbulence by means of an empirical model involving the velocity and depth of flow. Although other hydraulic properties have been considered by various subsequent investigators, for example, Churchill et al[5], Krenkel and Orlob[6] and Thackston and Krenkel[7], the predictive models most commonly used today[4,5] still explain stream reaeration in terms of the mean velocity and depth of flow.

It has long been recognized that all of the available predictive models relating K_2 to stream hydraulic properties leave something to be desired. Most of them incorporate theoretical assumptions that cannot be verified, none have been adequately field-tested, and each model appears to provide adequate predictions of K_2 for some streams but not others. As indicated earlier, the principal difficulty encountered in such attempts to relate stream reaeration capacity to the hydraulic properties has been that neither the reaeration capacity nor the associated degree of turbulence could be measured directly or independently.

As indicated in Section IV [see equation (4)] and derived earlier from simple considerations of the kinetics of gases[10], the reaeration rate coefficient, K_2, is directly

Preceding page blank

proportional to the rate of water surface replacement in a turbulent water system. Hence, "turbulence" refers here quite specifically to the rate of surface replacement, and a clear distinction must be made between stream hydraulic properties that are related to surface replacement (and reaeration) in a primary way, or cause it, and those hydraulic properties that may be related to "turbulence" (and reaeration) only in an indirect or secondary way. In any attempt to relate stream reaeration capacity to hydraulic properties it will be desirable to express the rate of water surface replacement in terms of the primary or causative hydraulic properties. In addition, it will be necessary to select or develop ways to measure those primary hydraulic properties with accuracy and without ambiguity.

Before proceeding to detailed tests of the available predictive models and, subsequently, to the development and testing of the new energy dissipation model, some further consideration of certain of the specific hydraulic properties appears desirable. This relates, in particular, to the real meaning of terms such as "mean velocity" and "mean depth", whether such properties are of primary or secondary importance in regard to surface replacement, and whether the field methods of observing such properties are adequate.

One of the real problems encountered in this research relates to the basic meaning of certain traditional measures of hydraulic properties. Stated another way, sometimes the very method of measurement of a hydraulic property, or the method of computing it, modifies its real meaning in the physical sense. For example, if we consider a section of a natural stream, the way in which we obtain the mean water depth affects its real meaning in terms of its relationship to the actual rate of water surface replacement. For instance, the model

$$\text{Depth} = \frac{\text{Occupied Channel Volume}}{\text{Surface Area}}$$

is valid only if there is complete and homogeneous mixing of all of the water in the channel, especially vertical mixing. To consider an extreme, in a stratified channel or reservoir the whole volume is separated into hydrodynamic regions, the depth that is directly involved in surface replacement (and reaeration) is much smaller than the above expression would imply, and reaeration of the lower region is virtually nil. In many natural streams of relatively small slope the water depth that is directly involved in surface replacement and reaeration is considerably smaller than the measurable whole depth of flow, due to poor vertical mixing.

Some of the hydraulic properties of natural watercourses are considered below, together with methods of observation or measurement and the resulting implications as regards reaeration capacity.

Velocity. Most of the available models for predicting reaeration capacity include the "mean velocity", either directly or indirectly, and at first glance it seems obvious that the rate of water surface replacement ought to be a function of the velocity. But on closer inspection two questions present themselves: first, how shall this "mean velocity" be measured, and secondly, does this method of observation affect the usefulness of the result as a measure of surface replacement? A third question, namely, is velocity a basic property that causes surface replacement, is perhaps the most important question of all.

There are at least two commonly used methods of obtaining the "mean velocity". The first involves direct physical measurement of the velocity at a number of locations in a stream cross-section by the use of a current meter; if enough such measurements are made, a reasonably accurate measure of the average forward velocity through that cross-section can be obtained. If, then, this procedure is repeated at a sufficient number of cross-sections in a specified length of stream channel, the results can be combined to obtain a reasonably accurate estimate of the mean forward velocity of flow that prevails throughout the length of the stream section. This procedure is subject to certain obvious sources of error relating especially to the statistical adequacy of the number of observations made in any one cross-section, the statistical adequacy of the number of cross-sections involved, and the accuracy of the current meter observations when forward velocities are relatively small. But in addition, and even more importantly, there would appear to be legitimate question as to whether the forward velocity is that velocity that is most nearly related to the rate of surface replacement.

The other commonly used method of obtaining the "mean velocity" involves measurements of the distance travelled and the time of flow. The distance travelled can be obtained readily and with quite adequate accuracy from USGS quadrangle sheets or by field survey; the time of flow can be measured with great accuracy by the use of dye tracers. The resulting "mean velocity", the distance divided by the time, is relatively precise because of the precision of the measures involved. Depending upon the degree of homogeneity and completeness of mixing in the channel, it is not necessarily the same "mean velocity" as that obtained by the first method outlined above, but it clearly reflects the actual forward velocity that is effective in the channel. Whether or not such a forward velocity adequately relates to the rate of surface water replacement is again open to serious question.

Both of the foregoing procedures for obtaining a representative mean velocity for a length of stream neglect the real velocity fluctuations that occur within the stream reach at changes in slope or cross-section. Yet, in terms of the real rate of surface water replacement, the variability of velocity, or the range of velocities, within a stream reach may well be of more significance than the magnitude of the mean velocity itself. Also, although velocity, or its variability, may well be *related* in some way to surface replacement and reaeration, it would not seem to be a primary hydraulic property, or one that is a basic *cause* of surface replacement. Rather, the velocity is the *result* of some other property such as channel slope, constrictions, etc., and in that sense is more of the nature of a secondary hydraulic property.

Thus, although a measure of stream velocity can be obtained as outlined above, and although such a measure may be a "mean" in the usual sense, there is real question as to its usefulness as a representation of surface replacement. Perhaps a more meaningful measure would be an estimate of the mean *vertical velocity* component in the stream channel, as this would seem to be more directly relatable to the rate of surface replacement. Again, however, the very method of observation could greatly affect the meaning and the usefulness of the result.

Depth. As reaeration is a direct function only of the rate of surface replacement, stream depth has importance only in terms of a possible relationship to the rate of surface replacement, and only then if mixing is complete and homogeneous. Although it seems unlikely that depth itself is in any way a direct cause of surface replacement, a brief review of the methods of observation and the meaning of the derived results is of interest.

One method of obtaining the "mean depth" has already been outlined, namely, the result of dividing the occupied channel volume by the whole surface area, and its meaning has been discussed. An effective channel volume may also be obtained as the product of flow and time of passage--this might lead to a more representative effective depth in some situations (stratified reaches) but not necessarily in others (short-circuiting). Another commonly considered method of observing the "mean depth" involves measurement of the dimensions of the stream cross-section by field survey, wherein the mean depth of the cross-section is obtained by dividing the observed cross-sectional area by the measured stream width. If an accurate measure of the "mean depth" of a length of stream channel is to be obtained by this means, a substantial number of cross-sections must be included for purposes of statistical adequacy. A substantial amount of field survey work is therefore involved. However, the result is subject to much the same criticism as was made for the volume/surface area method - the "mean depth" obtained is a measure of the effective depth only if there is complete and homogeneous mixing in the stream channel, and this requirement is not met in a large number of cases.

It should be noted here that although the term (A/V) appears in equation (4), Section IV, this term is not really to be construed as the reciprocal of the depth. Rather, the entire term (nA/V) must be considered as an entity, and its interpretation is best restricted to the derived meaning - it is the rate of surface replacement in cm^2/second/unit volume.

The various methods of obtaining an accurate measure of the mean depth of flow in a length of natural stream channel are tedious at best, even if there is complete and homogeneous mixing. In any event, the real meaning of such measures in terms of the rate of surface water replacement is not readily apparent, and it appears unlikely that depth itself has any causative relationship to surface replacement.

Slope. The physical slope of a natural stream channel, namely the decrease in elevation per unit of channel length, is readily observable by field survey, although the fieldwork may be somewhat tedious and time-consuming. Surprisingly, although the slope would appear to be an important hydraulic feature, such measurements are not commonly made or available. Indeed, intuitively the slope of the stream channel would appear to be more nearly a determining or a causative property than most others - it is an independent property except where engineering works have modified it, and properties such as the velocity and depth of flow are functions of the slope rather than vice versa. In essence, the steeper the channel slope, the more violent the tumbling action that creates water surface replacement, and, hence, it appears that the channel slope should not only be related to the rate of surface replacement but should, in fact, be a basic cause of surface replacement. As indicated above, it can be measured with entirely satisfactory accuracy.

Roughness. One other property that would seem to be important in terms of water surface replacement is the physical channel roughness, in the sense that a very rough rocky stream bed should create better vertical mixing than a smooth sandy stream bed. Of course, the bottom roughness cannot be measured directly or independently, and the available method of obtaining an estimate of bottom roughness, namely calculation by means of the Manning equation, is circuitous and subject to substantial error. In addition, the character of a stream bed, or its physical roughness, is not so independent a hydraulic property as might appear at first glance - in fact, the bottom character results from properties such as the velocity and the slope of the channel. Hence, although the bottom roughness may be related in some way to the degree of vertical mixing and the rate of surface replacement, it would not appear to be a basic property that independently *causes* surface replacement.

Certain of our experimental results have caused us to view the hydraulic properties in a somewhat different way that appears to have more promise in terms of developing a basic relationship between stream reaeration capacity and hydraulic properties. This point of view involves consideration of the relationship between surface replacement and energy dissipation. However, before proceeding to the development and testing of this energy dissipation model, the reaeration rate coefficients observed in these research studies will be compared to those predicted by use of the several available predictive models.

Time of Flow. Reaeration and stream self-purification are direct functions of time, and the time of flow within a stream reach is thus an important hydraulic property quite aside from any other consideration. In addition, however, the time of flow within a stream reach is a specific hydraulic characteristic of that reach, and represents the net effect of other hydraulic properties (e.g., slope, flow, velocity, etc.) that are related to turbulence and water surface replacement. Thus, even though it is clearly not a property that independently causes reaeration, the time of flow is particularly significant in that it ties together both reaeration and other stream hydraulic properties that are associated with turbulent mixing. With the introduction of the use of fluorescent dye tracers about a decade ago, accurate measurement of the time of flow of a stream has become a simple matter.

COMPARISONS WITH AVAILABLE PREDICTIVE MODELS

In order to determine the predictive capability of some of the previously available reaeration models, several of these models were tested by comparing the reaeration coefficients measured during the current study with values predicted by the models. The models selected for testing were the O'Connor-Dobbins model (4), the Churchill model (5), the Langbein-Durum model (14), the model proposed by Owens, Edwards, and Gibbs (16), and the Thackston-Krenkel model (7). Equation (9) was used to adjust each of these models to a standard temperature of 25°C. The forms of the predictive equations used in this comparison were as follows:

O'Connor-Dobbins $K_2 = 0.573\ V^{0.5}/H^{1.5}$

Churchill, et al $K_2 = 0.543\ V^{0.969}/H^{1.673}$

Langbein and Durum $K_2 = 0.353\ V/H^{1.33}$

Owens, Edwards and Gibbs $K_2 = 1.020\ V^{0.97}/H^{1.85}$

Thackston-Krenkel

$$K_2 = 1.122\ (1+ (V/[gH]^{1/2})^{1/2})\ (Sg/H)^{1/2}$$

The adequacy of each of these five models was tested by comparing the predicted values of K_2 with those measured during the tracer studies. The hydraulic parameters used in the predictive equations were determined by detailed hydraulic measurements on the various rivers. The hydraulic measurement techniques have been described in Section V. The measurements made on the South, Flint, and Chattahoochee Rivers during the hydraulics study were adjusted by the procedure described in Section V to make the values of the hydraulic parameters consistent with the discharge rates in the streams during the tracer studies. Such adjustments were not possible for the Patuxent and the Jackson River studies, and typical values of the hydraulic parameters were used for these streams.

The five predictive equations taken together include only three hydraulic terms, velocity (V), depth (H), and slope (S). The velocity was measured directly during each tracer release by dividing the distance between sampling stations by the time of flow as measured by the dye tracer. Hence, the only two parameters that were adjusted were depth and slope. Discharge rates measured during the hydraulic studies were, in most cases, not greatly different from those measured during the tracer studies and, consequently, the required adjustment in depth at each 500-foot cross section was generally small (0.1 to 0.2 feet). As a result, the values of depth used in the predictive equations for the South, Flint, and Chattahoochee Rivers, which were the average values of the depths at each of the 500-foot cross sections between sampling stations, are considered to be quite accurate. The slope was determined by taking the difference between the water surface elevations at upstream and downstream sampling stations, as adjusted for flow rates, and dividing the difference by the distance between stations. The values of slope used in the predictive equations, like the values of depth, are thus also taken to be quite accurate. The unadjusted values of depth and slope used for the Patuxent and Jackson River studies are believed to be very close to the values existing at the time of the tracer studies.

The test of the predictive equations was based on a correlation and regression analysis. Regression lines of the form shown below were used to relate predicted and measured values of K_2.

$$Y = a_o + a_1 X$$

In this regression equation the values of K_2 calculated from the predictive equations are represented by X, and Y is the measured value of K_2. In addition to determining the slope (a_1) and the intercept (a_o), the correlation coefficient (r_{xy}) was computed for each predictive equation. The values of a_o, a_1, and r_{xy}, as determined by a least squares fit of the predicted and observed reaeration data, were used as a measure of the capability of each of the five equations tested. For a good model, that is, an equation capable of predicting values of the reaeration coefficient close to the values observed in the field, the value of a_o will be near zero and the value of a_1 will be near unity. The possible range of the correlation coefficient is from -1.0 to +1.0, and a value close to +1.0 indicates that the variation of the predicted values of K_2 about the regression line is small.

The values of a_o, a_1, and r_{xy} computed for each model are shown in Table 27. Two sets of data were used from both the Flint River and the South River. A total of 89 values of K_2 were measured in the Flint River. Five of these values were measured at the two waterfalls on the Flint (two values between stations 1P and 1 and three between 2P and 2), and could not be included in the text since the

Table 27

Statistical Test of Selected Predictive Models

Flint River

Model	(84 observations)			(43 observations)		
	a_o	a_1	r_{xy}	a_o	a_1	r_{xy}
O'Connor	-0.06	1.14	0.68	0.14	0.16	0.31
Churchill	-0.02	1.53	0.75	0.14	0.24	0.38
Langbein	-0.09	2.90	0.74	0.12	0.47	0.41
Owen	-0.01	0.73	0.76	0.14	0.11	0.36
Thackston	0.06	0.72	0.34	0.06	0.42	0.53

South River

Model	(96 observations)			(91 observations)		
	a_o	a_1	r_{xy}	a_o	a_1	r_{xy}
O'Connor	0.34	-0.03	0.00	0.20	0.04	0.04
Churchill	0.40	-0.26	-0.06	0.20	0.05	0.06
Langbein	0.42	-0.48	-0.07	0.19	0.10	0.08
Owen	0.39	-0.13	-0.05	0.20	0.04	0.08
Thackston	-0.44	3.03	0.90	-0.06	1.25	0.67

Patuxent River

Model	(30 observations)		
	a_o	a_1	r_{xy}
O'Connor	0.08	0.19	0.50
Churchill	0.09	0.25	0.53
Langbein	0.09	0.46	0.56
Owen	0.10	0.12	0.51
Thackston	0.02	0.54	0.44

Table 27 (con't)

Jackson River

Model	(80 observations) a_o	a_1	r_{xy}
O'Connor	0.12	0.27	0.14
Churchill	0.12	0.52	0.21
Langbein	0.10	0.84	0.24
Owen	0.12	0.27	0.19
Thackston	0.11	0.18	0.20

Chattahoochee River

Model	(30 Observations) a_o	a_1	r_{xy}
O'Connor	0.05	-0.05	-0.06
Churchill	0.05	-0.05	-0.06
Langbein	0.05	-0.04	-0.04
Owen	0.05	-0.03	-0.06
Thackston	0.03	0.25	0.10

available equations are not able to predict K_2 values for such situations. The second set of data used from the Flint contains 43 values and is a subset of the 84 values used in the first test. All reaches of the Flint which include waterfalls or rapids were excluded from this subset. A total of 96 values of K_2 were measured on the South River and all 96 are included in the first test. In the second test those values of K_2 measured at Panola Shoals (between stations K and L) and those measured over a reach containing rapids(G* to T2) were eliminated.

When the data set which includes the 84 values from the Flint is used to test the models, the O'Connor-Dobbins model does a better job of predicting the observed values than do the other four models. All of the models yield values of a_o close to zero. (The term "close" is, of course, a qualitative description. The value of a_o might be compared to the average value of the observed K_2's in order to judge the relative significance of the intercept. In the present case the average of the 84 observed values of K_2 is 0.38 and the range is from 0.03 to 2.49. Thus, the values of the intercepts shown in Table 27 range from about 3% to about 24% of the average.) The slope of the O'Connor-Dobbins model is close to unity, while the Churchill model and the Langbein model tend to underpredict the observed values and the Owen model and the Thackston model tend to overpredict. An examination of the first four models listed above shows that they are all of similar form but that the coefficient in the Owen model is two to three times that in the other three models. Thus, the Owen model can be expected to predict higher values, particularly when compared to the Churchill and Langbein models which have similar values of the exponents. All of the models, with the exception of the Thackston model, produce correlation coefficients in the range 0.68 to 0.76. The Thackston model produces a correlation coefficient of only 0.34 for this set of data.

When all reaches on the Flint which contain waterfalls and rapids are eliminated, the test shows that all of the models tend to overpredict the higher observed values and to underpredict the lower values of K_2. The range of observed values of K_2 in this subset is from 0.03 to 0.53 and the average value is 0.17. The Thackston model produces the highest correlation coefficient for this reduced set of Flint River K_2's (r_{xy} = 0.53).

When the set of K_2 values measured on the South is considered, it is evident that only the Thackston model is capable of predicting values reasonably close to those measured. All of the other four models produce negative values of a_1 and r_{xy} when all 96 values are used in the computations. This indicates that the observed values tend to increase as the predicted values decrease. The extremely low values of r_{xy} for the first four models indicate that there is really no correlation between the observed and predicted values and that the negative values of a_1 are not significant. The high correlation coefficient produced by the Thackston model ($r_{xy} = 0.90$) is associated with values of a_o and a_1 significantly different from the "good" values of zero and unity, respectively. The value of -0.44 for a_o and 3.03 for a_1 indicate that the Thackston model strongly underpredicted the higher observed values of K_2. The observed range of K_2's predicted by the Thackston model was from 0.06 to 0.33.

Removing the higher observed values of K_2 from the test data for the South River improved the values of a_o, a_1, and r_{xy} only slightly for the first four models. Some improvement is also seen to occur in the slope and intercept of the Thackston model but the tendency of the model to underpredict the high observed values and to underpredict low values is still present.

All of the models tended to overpredict the values of K_2 observed on the Patuxent. The average observed value of K_2 was 0.14, thus, the values of a_o (the intercept) for the first four models represent values almost as large as the average. The Thackston model has the largest value of a_1, 0.54, and hence, tends to overpredict by a smaller amount than do the other models. The correlation coefficient for the Thackston model was smaller than for the other four models, but all the values for all five models were similar (0.44 to 0.56).

The tendency of the models to overpredict observed values of K_2 continues to persist when the values observed and predicted for the Jackson River are examined. On the basis of the Jackson data there is no reason to prefer one model over any other. All produce low correlations (r_{xy} ranging from 0.14 to 0.24). The values of a_o range from 0.10 to 0.12 as compared to an average value of K_2 equal to 0.15. Thus, most of the regression lines for this river are essentially horizontal lines through the mean value of K_2 observed.

The Thackston model is the only one of the five that produced positive values of a_1 and r_{xy} when the models were tested with the Chattahoochee data. However, the regression line for the Thackston model yields a correlation coefficient of only 0.102, and the value of a_o (0.03) is near the average of the observed values (0.04).

The test of the five selected models using seven sets of data from five rivers of varying characteristics indicates that none of the models are capable of accurately predicting the values of K_2 observed during tracer studies on these rivers. In most cases, the regression line fitted to the observed and predicted data had a slope less than unity, indicating a tendency to overpredict observed values, and no model was consistently capable of yielding high correlation coefficients.

ENERGY DISSIPATION MODELS - THEORY

Consider a length of natural stream channel between two points, 1 and 2. The usual one-dimensional energy equation indicates that the amount of energy expended in ft-lbs per lb of water between the two points is

$$(E_1 - E_2) \simeq (\frac{V_1^2}{2g} + z_1 + H_1) - (\frac{V_2^2}{2g} + z_2 + H_2) \qquad (42)$$

where V is the velocity in ft/sec, z is the elevation of the stream bed above mean sea level in ft, H is the depth of water in ft, and g is the gravitational constant in ft/sec^2.

Rearranging terms,

$$(E_1 - E_2) \simeq (\frac{V_1^2 - V_2^2}{2g}) + \Delta h \qquad (43)$$

where

$$(z_1 + H_1) - (z_2 + H_2) = \Delta h \qquad (44)$$

and Δh is the change in water surface elevation between points 1 and 2.

With few exceptions, the difference in velocity head, $(V_1^2 - V_2^2)/2g$, is negligibly small compared to the change in elevation head, Δh. Hence, for most reaches of stream

$$(E_1 - E_2) \simeq \Delta h \qquad (45)$$

for practical purposes.

The rate of energy expenditure is just the amount of energy expended per unit time, or

$$\left(\frac{E_1 - E_2}{t_f}\right) = \left(\frac{\Delta h}{t_f}\right) \tag{46}$$

where t_f is the time of flow from 1 to 2.

It has also been shown in our earlier work that

$$K_2 = an\frac{A}{V} \tag{4}$$

where K_2 refers to the gas transfer coefficient for any gas, the constant, a, refers to the molecular properties of the gas and the quality of the water, n is the number of surfaces of area A replaced per unit time, and V is the whole volume of water. The product $(n\frac{A}{V})$ is therefore just the rate of surface replacement in cm^2 per second per cm^3 of volume, if metric units are employed.

It appears logical to suppose that the rate of water surface replacement will be related to the rate of energy dissipation, probably in a simple and direct way. Accordingly, the following relationship has been postulated:

POSTULATE: The rate of water surface replacement is proportional to the rate of energy dissipation in open channel flow.

Using the expressions given in equations (4) and (46) above, the postulate may be expressed as follows:

$$\left(n\frac{A}{V}\right) = b\left(\frac{\Delta h}{t_f}\right) \tag{47}$$

where b is the necessary proportionality constant.

It now follows from equations (4) and (47) that

$$K_2 = c\left(\frac{\Delta h}{t_f}\right) \tag{48}$$

where c = ab

Equation (48) is our basic model relating the reaeration coefficient, K_2, to the stream hydraulic properties. The coefficient K_2 actually refers to any gas, including krypton as well as oxygen, the only difference being the numerical magnitude of the constant, c. The hydraulic properties Δh and t can be measured directly and independently, as well as with quite satisfactory accuracy, for any length of stream channel. Hence, equation (48) and its underlying postulate can be tested directly with field observations. However, before doing so, one other useful expression will be derived.

For the length of stream between points 1 and 2, equation (5) from Section IV indicates that for desorption of the tracer gas

$$C_2 = C_1 e^{-K_2 t_f}$$

where C_1 and C_2 are the concentrations of dissolved tracer gas at points 1 and 2. Replacing K_2 by its equivalent from equation (48), we obtain

$$y = \frac{C_2}{C_1} = e^{-c\Delta h} \qquad (49)$$

where y is just the decimal fraction of dissolved tracer gas remaining at point 2. It follows also that

$$(1 - y) = z = (1 - e^{-c\Delta h}) \qquad (50)$$

where z is now the decimal fraction of dissolved gas that has been lost between points 1 and 2. Equations (49) and (50) refer directly to the tracer gas, krypton, but may also be used to refer to the decimal fractions of the DO deficit remaining and satisfied, respectively.

Equation (50) is of very strong interest. It states, simply, that gas transfer in a turbulent natural stream is dependent only upon the change in water surface elevation. In other terms, at a given water temperature the amount of tracer gas that will be lost to the atmosphere in a specific length of stream channel, or the amount of DO deficit that will be satisfied, can be predicted on the basis solely of the change in water surface elevation between the upstream and downstream ends of the length of stream. Alternatively, the numerical magnitude of K_2 can be predicted on the basis of the change in water surface elevation and the time of flow, according to equation (48).

It is emphasized that the foregoing equations have been developed with the implicit assumption of unrestrained mixing and surface replacement. Departures from this condition in real stream situations will cause corresponding discrepancies between the observed gas transfer characteristics and those predicted by equations (48) and (50). Such departures might involve, for example, appreciable short-circuiting or stratification. An example of such a hydraulic situation has already been cited in regard to the long, deep pool above Panola Shoals in the South River.

Other Models. Although the two energy dissipation models represented by equations (48) and (50) are regarded as the basic expressions relating stream hydraulic properties to reaeration capacity, it should be noted that they also lead to other models that may prove to be of interest. As a single example, equation (48) suggests that the rate of energy dissipation can be represented also by the product of a slope and a velocity. Specifically,

$$\left(\frac{\Delta h}{t_f}\right) = \left(\frac{\Delta h}{L}\right) \times \left(\frac{L}{t_f}\right) \qquad (51)$$

in which L is the length of a reach of stream. The term $(\Delta h/L)$ is thus the slope of the water surface, and (L/t_f) is the mean velocity determined by the distance travelled and the time of flow. The reaeration rate coefficient, K_2, may thus be expected to be proportional to the product of the slope of the water surface and the mean velocity as defined in equation (51).

Other such relationships between reaeration and usual hydraulic properties may also be developed similarly from the basic models given by equations (48) and (50), but such relationships need not be provided here. Instead, the experimental evidence in support of the basic models is presented below.

ENERGY DISSIPATION MODELS - OBSERVED RESULTS

The detailed field study results reported in Appendix AIV are used here for the purpose of testing the validity and accuracy of the energy dissipation models, equations (48), (49) and (50). The five rivers involved will be taken in the order of their appearance in Section VI, namely, the Flint, South, Patuxent, Jackson and Chattahoochee. In each case, the basic energy dissipation models for reaeration will be tested according to standard statistical procedures, and the results also presented in graphical form for ease of interpretation.

Flint River. Reference to Appendix AIV indicates that a total of 89 observations of the reaeration capacity of reaches of the Flint River were made during the field tracer studies. Of these, six observations cannot be used here because the elevation of Station 7 was not accurately measured during the field physical studies--the levelling party proceeded only part of the distance between Stations 6 and 7 before discontinuing operations on the Flint. Hence, the magnitude of Δh for the reaches 4-7, 5-7 and 6-7 is not accurately known for Dumps V and XII, and those six observations cannot be used here. This does not detract from their use earlier, however, in tests of the magnitude of K_2, as that depends only upon the observed gas loss and time of flow, both of which are accurately known.

Figure 45 presents all of the individual observed results (see Appendix IV) for the Flint River in a form suitable for interpretation in terms of equation (50). The percent loss of tracer gas has been plotted on natural scales against the water surface elevation change, Δh, in feet. As may be seen, the data describe an exponential curve of the form predicted by equation (50). The water surface elevation change is a measure of the energy expended in the reach of stream in each case, as outlined earlier, and the observed curve thus provides powerful visual support of the energy dissipation model given by equation (50).

For purposes of statistical testing, the data shown in Figure 45 have been plotted in the form required by equation (49). If the percent tracer gas remaining is plotted against Δh on semilog scales, equation (49) predicts that a straight line should result, and the degree of correlation between the logarithm of the percent gas remaining and the water surface elevation change can thus be readily obtained by usual methods. For the 83 observed results shown in Figure 46, a correlation coefficient of 0.957 was found, indicating that 92 percent of the variation in the logarithm of percent tracer gas remaining has been explain-

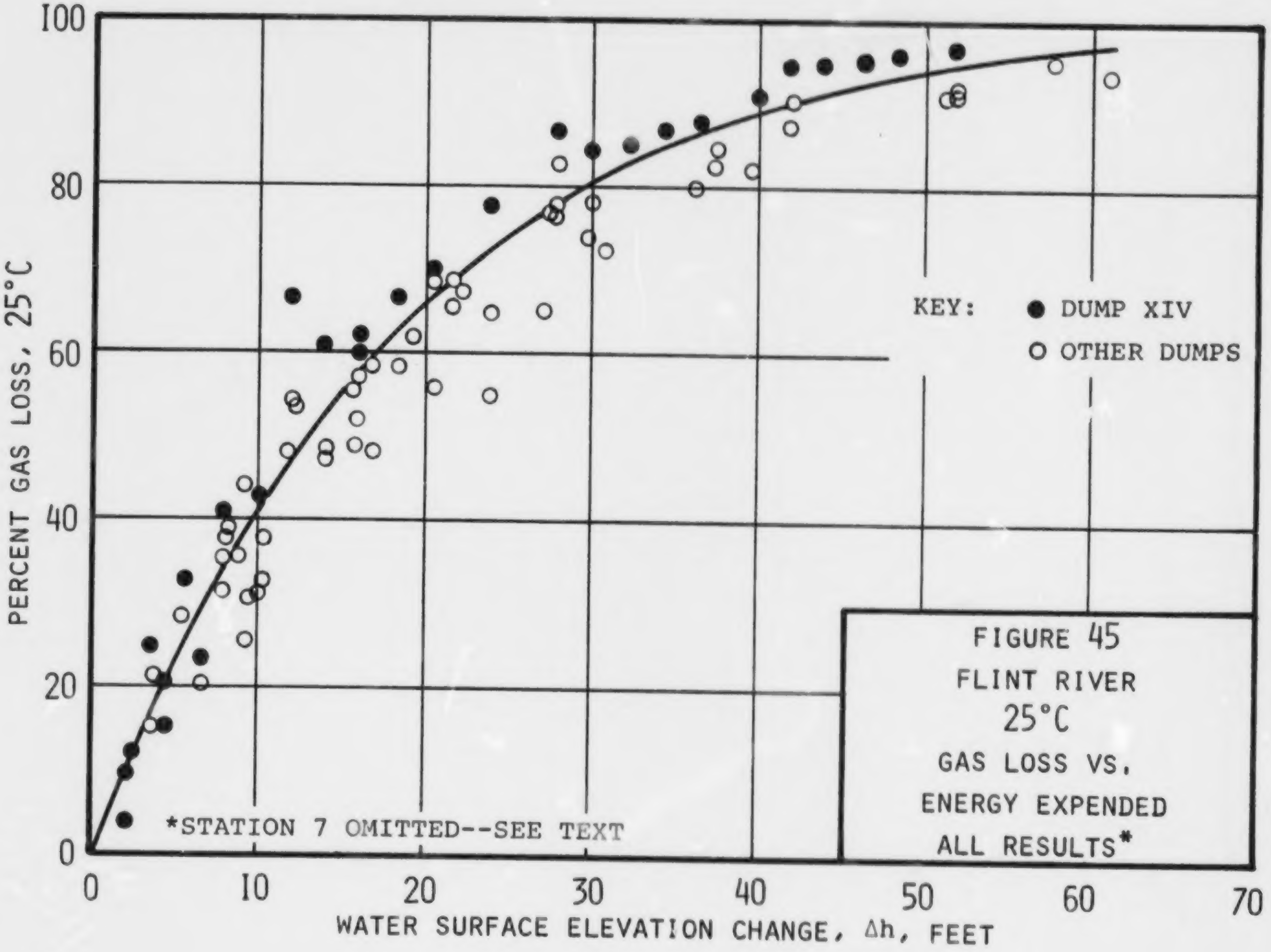


FIGURE 45
FLINT RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
ALL RESULTS*

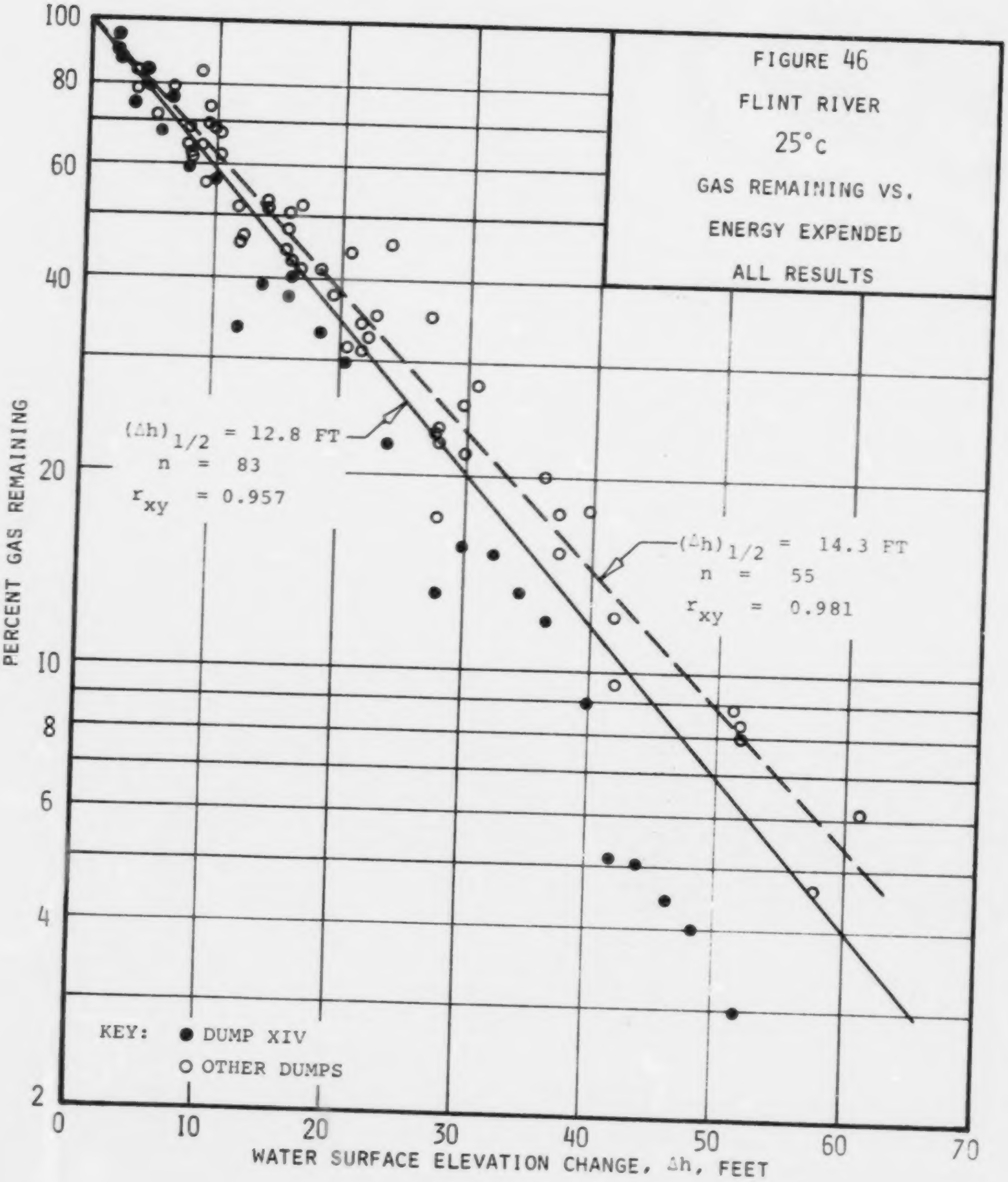


FIGURE 46
FLINT RIVER
25°C
GAS REMAINING VS.
ENERGY EXPENDED
ALL RESULTS

ed in terms of the relationship with Δh predicted by equation (49). When the regression line was forced through the origin (100 percent gas remaining at $\Delta h = 0$), as required by the theory, the magnitude of the correlation coefficient did not change, but remained 0.957.

For the regression line forced through the origin, the correlation analysis yielded a negative slope of 0.0543. This is the numerical magnitude of c in equation (49); it is referred to here as c_o, to indicate that it is associated with the regression line forced through the origin. This observed value of c_o is more readily interpreted and understood in terms of a half-height. The half-height is that numerical value of Δh that is associated with exactly 50 percent tracer gas remaining. It is readily shown that the half-height, $(\Delta h)_{1/2}$, can be found in any case from the relation

$$(\Delta h)_{1/2} = \frac{0.693}{c_o} \qquad (52)$$

Referring to the data at hand

$$(\Delta h)_{1/2} = \frac{0.693}{0.0543} = 12.8 \text{ feet}$$

Hence, in the case of these Flint River data, 50 percent of the tracer gas remained dissolved in the water after the river had dropped 12.8 feet, 25 percent remained after a total fall of 25.6 feet, 12.5 percent remained after a fall of 38.4 feet, etc. Conversely, 50 percent of the tracer gas was lost to the atmosphere in the first 12.8 feet of fall, a total of 75 percent was lost in 25.6 feet of fall, etc.

Referring to equation (48), and recalling that $K_{kr} = 0.83 K_{ox}$, it is readily shown that

$$[(\Delta h)_{1/2}]_{ox} = 0.83[(\Delta h)_{1/2}]_{kr}, \qquad (53)$$

whence the foregoing results are directly convertible to dissolved oxygen deficit terms. The half-height of 12.8 feet for dissolved krypton converts to a half-height of 10.6 feet for DO deficit, by equation (53). Hence, in this case, 50 percent of the existing DO deficit would be satisfied by reaeration in 10.6 feet of fall, 75 percent would be satisfied in 21.2 feet of fall, etc., if there were no other sources of dissolved oxygen consumption.

Figures 45 and 46 also illustrate the variations that may occur from one time to another in a stream like the Flint. Referring to these figures, the data obtained from Dump XIV have been blacked in so as to make them stand out on the graphs. In each case, the data for Dump XIV are clearly different from the rest of the results in regard to the curve or line of best fit. Referring to Figure 45, the Dump XIV results are clearly high, showing greater tracer gas loss than usual; in Figure 46, the slope of the line of best fit is clearly steeper for the Dump XIV data taken alone.

Dump XIV was the only Flint River study conducted on a weekend (a Saturday), all of the other tracer releases having been conducted on weekdays. As a result, the degree of pollution from the single source (the Flint River STP) was lower during Dump XIV than on weekdays, and so was the river flow, and the times of flow were substantially longer for Dump XIV. The data for Dump XIV alone will be discussed below, but the effect of the lower degree of pollution is clear from Figures 45 and 46.

Referring to Figure 46, as indicated above, for all 83 results a correlation coefficient of 0.957 and a half-height of 12.8 feet were found. If the 28 results obtained in Dump XIV are excluded, the remaining 55 observations have a half-height of 14.3 feet and a correlation coefficient of 0.981 for a line forced through the origin, and the spread of data is clearly reduced. Hence, the usual (weekday) half-height is taken to be 14.3 feet, rather than 12.8 feet, and the half-height for satisfaction of the DO deficit under weekday pollution conditions is 11.9 feet, according to equation (53), rather than the 10.6 feet given earlier.

As noted earlier in Section VI, Dump XIV was conducted especially for study of gas transfer in the rapids section above Station 1P, as well as to obtain additional results for the upper reaches of the Flint. Hence, a relatively large number of sampling stations was involved, and a larger than usual number ($n = 28$) of observed results was obtained. Figures 47 and 48 show the 28 results for Dump XIV taken above. Figure 47 shows the relationship between percent loss of tracer gas and water surface elevation change, as predicted by equation (50). The data for this

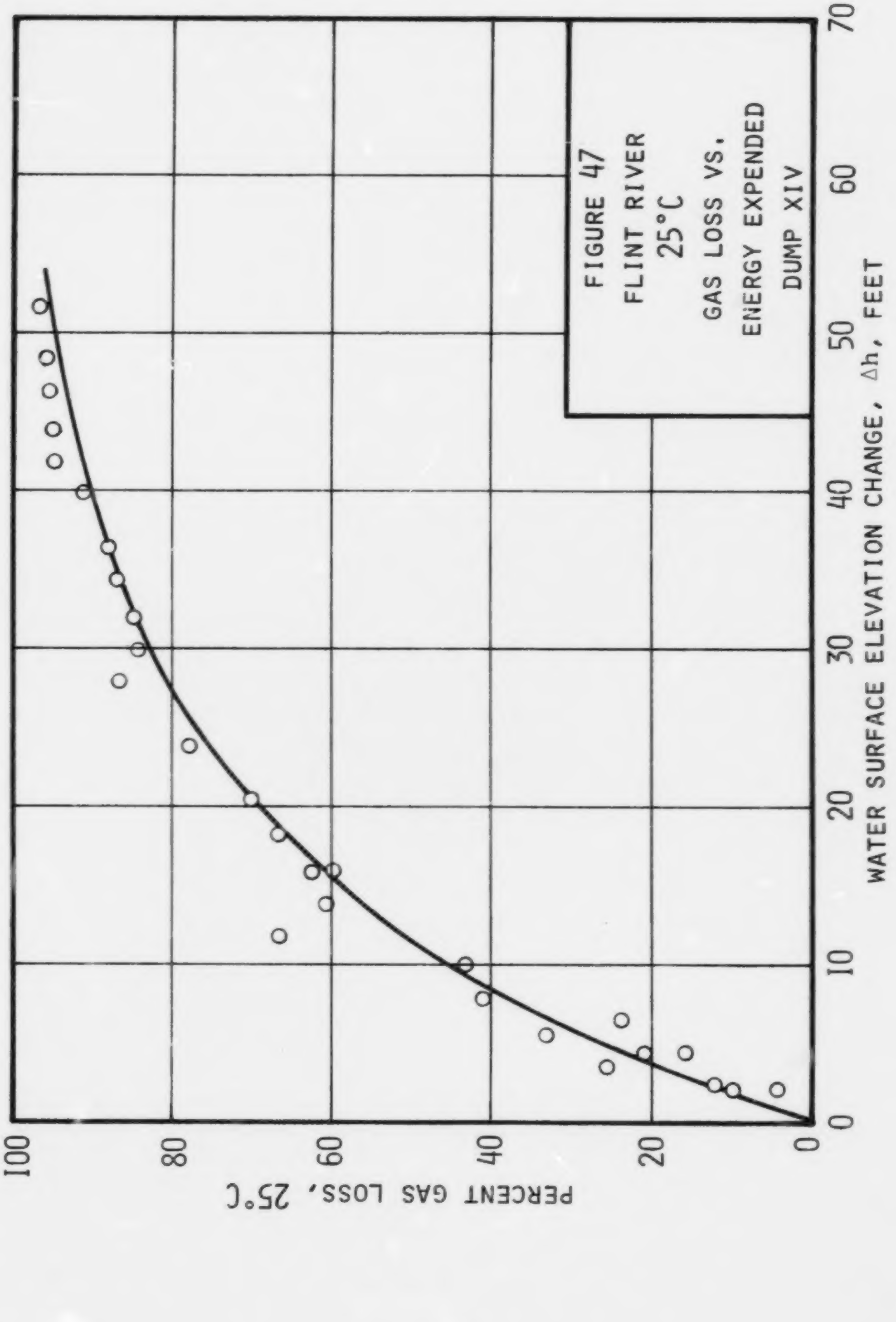


FIGURE 47
FLINT RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
DUMP XIV

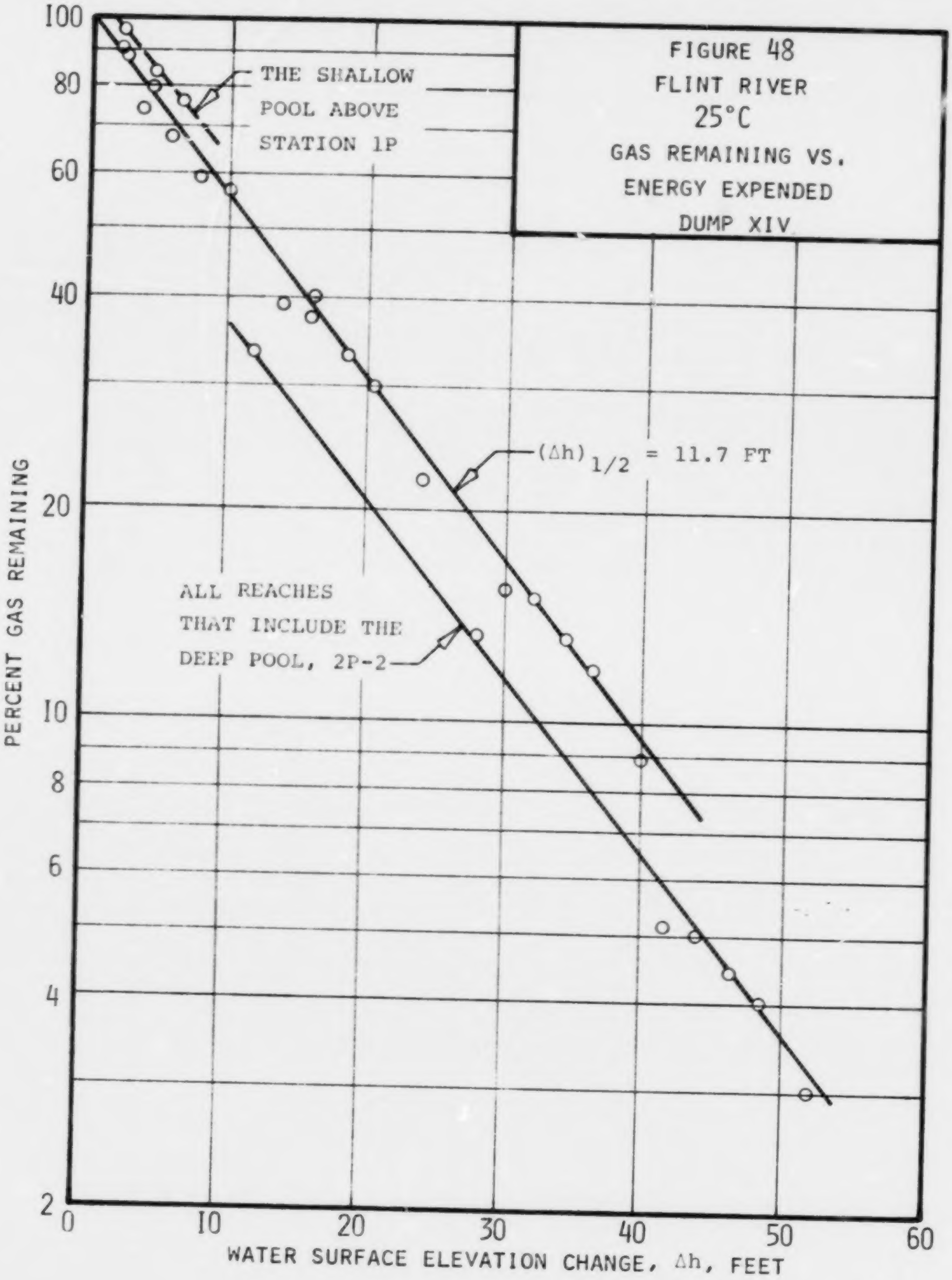


FIGURE 48
FLINT RIVER
25°C
GAS REMAINING VS.
ENERGY EXPENDED
DUMP XIV
THE SHALLOW POOL ABOVE STATION 1P
(Δh)1/2 = 11.7 FT
ALL REACHES THAT INCLUDE THE DEEP POOL, 2P-2
PERCENT GAS REMAINING
100
80
60
40
20
10
8
6
4
2
0
10
20
30
40
50
60
WATER SURFACE ELEVATION CHANGE, Δh, FEET

single tracer study are highly consistent, again providing powerful support of the energy dissipation models.

Figure 48 shows the same 28 observations for Dump XIV plotted in the form required by equation (49), namely, the logarithm of the percent gas remaining vs. Δh, or energy expended. A regression line forced through the origin has a high degree of correlation (0.991) and a half-height for krypton of 10.4 feet. However, upon closer examination of the data certain finer details stand out and are of interest. As may be seen, the data array themselves in a set of parallel lines all having the same slope associated with a half-height of about 11.7 feet, still substantially lower than the 14.3 feet corresponding to the usual weekday pollution level. The effect of the pools and falls in modifying the reaeration capacity is clarified by Figure 48.

Referring to Figure 48, the main set of results describes a straight line that passes through the origin, as expected from equation (49). However, a separate set describes a parallel line that is well apart, and below, the first line. This separate set of seven results represents all of the study reaches that include the deep pool, reach 2P-2, below the second waterfall. This same pattern is reproduced in earlier Dumps (II and III). Specifically, the data shown in Figure 48 indicate that for the reach 2P-2, which has a Δh of 11.85 feet, the observed gas remaining (33.4 percent, from the lower line) is considerably less than the expected gas remaining (50 percent, from the main line, which passes through the origin). In other terms, the observed gas loss in the reach 2P-2 was 66.6 percent instead of the expected 50 percent, and this is reflected in all reaches that include the fall and pool. In essence, these results indicate clearly that gas transfer in the deep pool below the second waterfall is enhanced by the action that takes place as the result of the water falling into the pool. Whether the additional gas transfer is due to air entrainment or simply to repetitive circulatory vertical mixing in the pool cannot be determined from these results, but the added effect on gas transfer is evident.

Although it is less obvious from Figure 48, another pool effect appears to be identifiable in terms of tracer gas losses. Referring to Figure 48, the dashed line at the top left represents as nearly as possible the long shallow pool immediately above the first waterfall. The three points represent the reaches between the rapids section immediately above this pool and the lower end of the pool, Station 1P. These data appear to indicate that gas loss in this pool was somewhat lower than it should have been--

possibly due to poor mixing and some underflow in this pool. However, that conclusion must remain in doubt, as the observable difference is not large and this particular pool (reach R-1P) was not studied specifically in other tracer releases.

Figures 49 and 50 show similar curves for the main study reaches, with a mean value shown for reaches having two or more observed results. All results for the main study reaches are included, so that Figures 49 and 50 are comparable to Figures 45 and 46. As may be seen, the fits are excellent, and the spread of results has been reduced considerably by the use of average values for each main study reach.

The foregoing results and analyses provide a clear and positive demonstration of the validity and basic nature of the energy dissipation models, equations (49) and (50), as regards the Flint River studies. The relationship predicted by equation (48) between K_{ox} and the rate of energy expenditure, $(\Delta h/t_f)$ has also been subjected to statistical analysis, using the individual observed values of K_{ox} (corrected to 25° C) and of $(\Delta h/t_f)$ provided in Appendix AIV. The results and their interpretation in terms of equation (48) are shown in Figures 51, 52 and 53. These figures show the results for values of $(\Delta h/t_f)$ less than 12.0, in order to avoid the scale distortion that would result from inclusion of the very high values (25.9 to 184) associated with the rapids section and the two waterfalls. Instead, for reaches having $(\Delta h/t_f)$ greater than 12.0, the observed and predicted values of K_{ox} are shown in tabular form.

Figure 51 shows the 74 results associated with a $(\Delta h/t_f)$ less than 12.0. For these 74 observations, which do not include the rapids or the two waterfalls, a correlation coefficient of 0.931 was obtained, and a slope of 0.0635/ft, for a regression line forced through the origin as required by equation (48). The correlation coefficient for a regression line with a nonzero intercept was also 0.931, and the slope only slightly different (0.0629/ft).

For all 83 individual observed results, which include the rapids section above Station 1P and the two waterfalls, 1P-1 and 2P-2, a correlation coefficient of 0.982 was obtained, and the regression line slope was 0.0702/ft. A regression line forced through the origin had the same correlation coefficient (0.982) and a slope of 0.0699/ft.

Referring to Figure 51, the data obtained from Dump XIV have again been blacked in so as to make them stand out

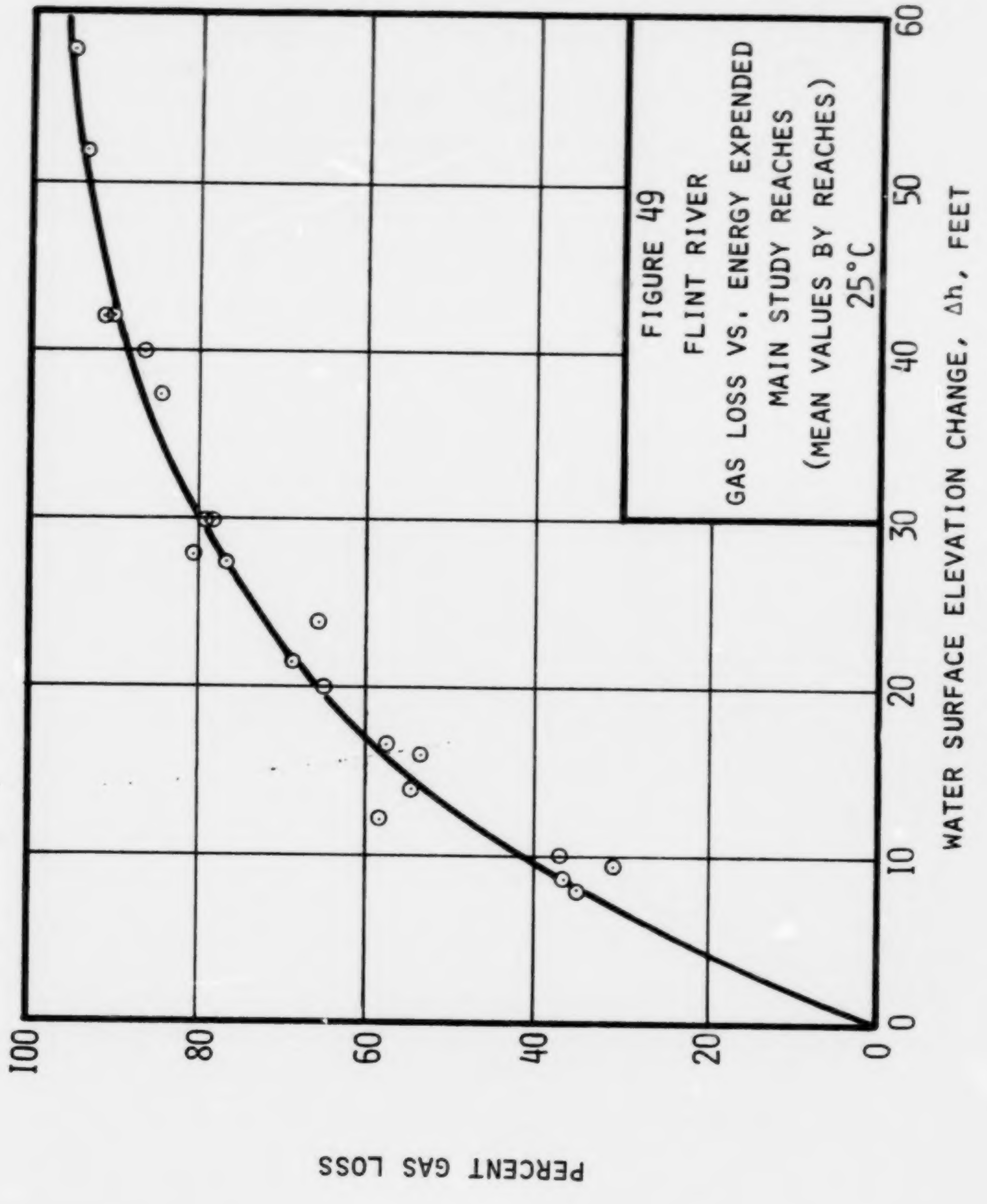


FIGURE 49
FLINT RIVER
GAS LOSS VS. ENERGY EXPENDED
MAIN STUDY REACHES
(MEAN VALUES BY REACHES)
25°C

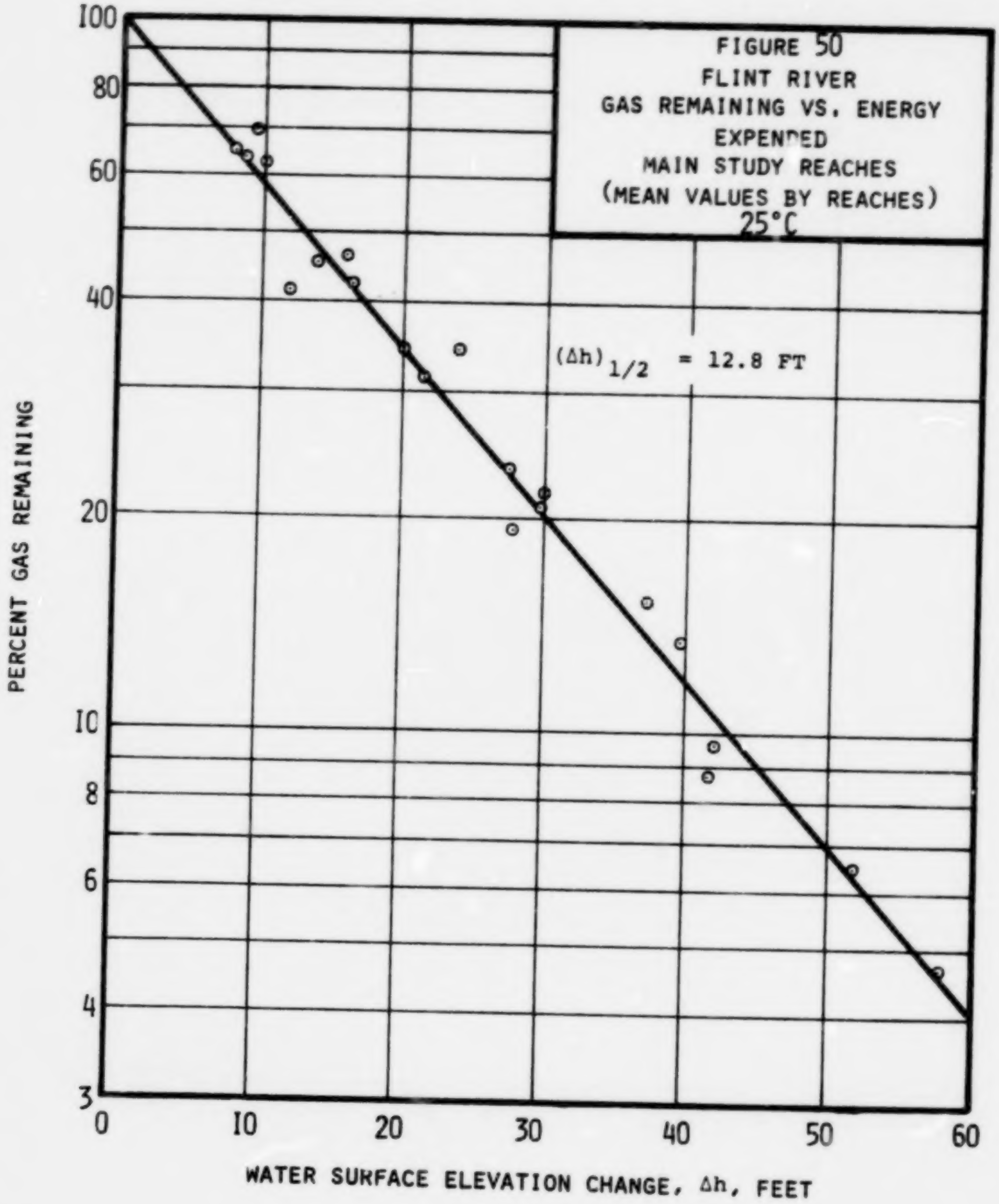


FIGURE 50
FLINT RIVER
GAS REMAINING VS. ENERGY EXPENDED
MAIN STUDY REACHES
(MEAN VALUES BY REACHES)
25°C
(Δh)1/2 = 12.8 FT
PERCENT GAS REMAINING
100
80
60
40
20
10
8
6
4
3
0
10
20
30
40
50
60
WATER SURFACE ELEVATION CHANGE, Δh, FEET

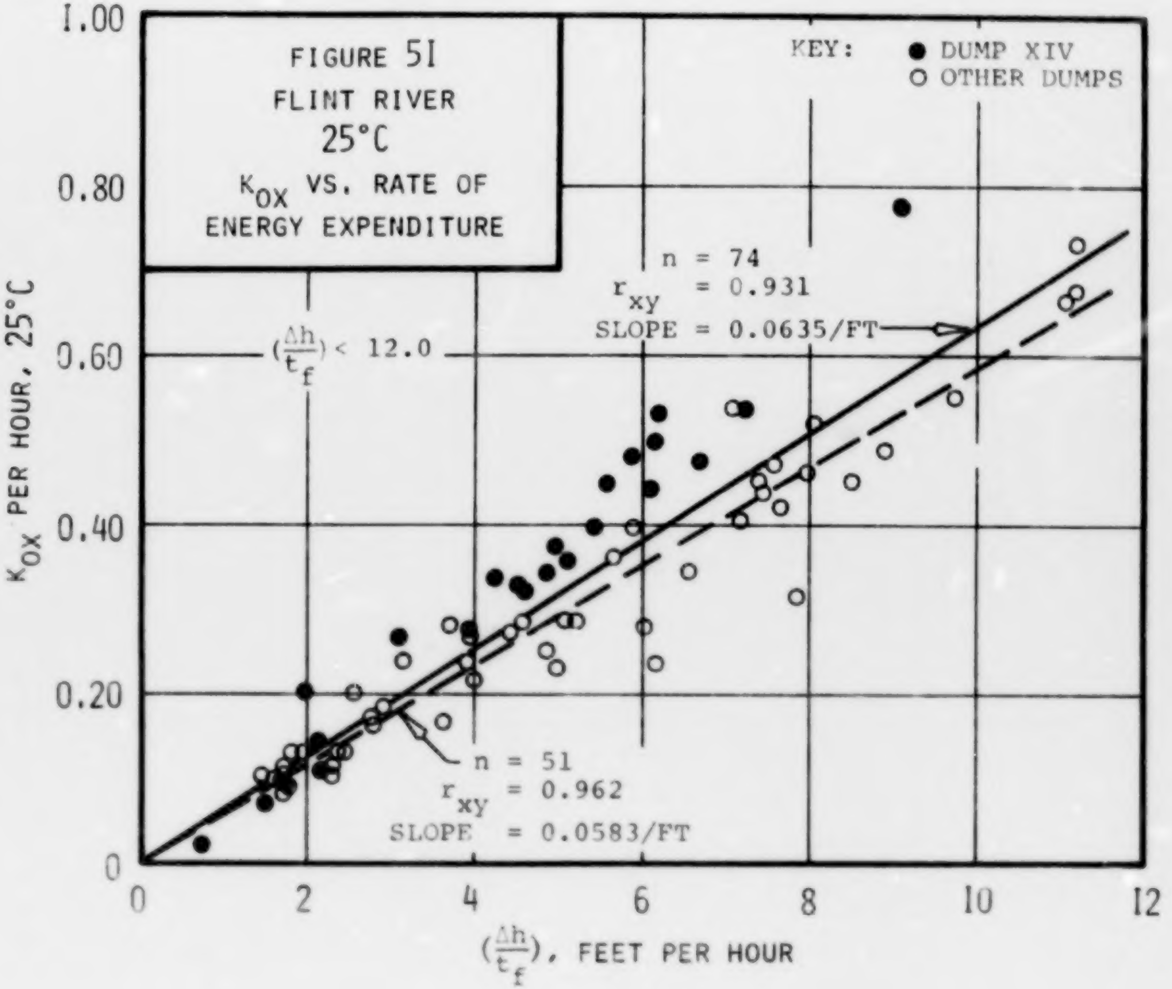


FIGURE 51
FLINT RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE

on the graph. Again, they are clearly different from the rest of the results in regard to the slope of a line of best fit, and demonstrate the effect on K_{ox} of reduced pollution during Dump XIV. When the 28 results obtained from Dump XIV are eliminated from the total of 83, the remaining 55 results have a correlation coefficient of 0.995, and the slope of the regression line forced through the origin is 0.0585/ft. Four of these 55 results have a $(\Delta h/t_f)$ greater than 12.0, and when they are eliminated, the remaining 51 observations yield a correlation coefficient of 0.962 and a slope for the regression line forced through the origin of 0.0583/ft. This latter line is shown as a dashed line in Figure 51. As outlined earlier, it represents the usual (weekday) pollution condition of the Flint River during these studies.

Figure 52 shows the relationship between K_{ox} and the rate of energy dissipation for the data of Dump XIV taken alone, as required by equation (48). For the 23 observed results associated with a $(\Delta h/t_f)$ less than 12.0, the correlation coefficient is 0.978 and the slope 0.0778/ft for a regression line forced through the origin. For the regression line with a nonzero intercept the correlation coefficient of 0.982 is only very slightly different. For values of $(\Delta h/t_f)$ greater than 12.0, the five additional results are tabulated in Figure 52. As may be seen, the correspondence between observed and predicted values of K_{ox} is very good. The reaches 1P-1 and 2P-2 are the two waterfalls, and the reaches R1-R2, R2-R3 and R1-R3 represent the rapids section above Station 1P. In agreement with the results shown earlier in Figure 48, for the reach 2P-2 the predicted value of K_{ox} is considerably lower than that observed, indicating the additional effect of the waterfall into the deep pool. Also, the dashed line at the lower left of Figure 52 shows the same three observations thus designated in Figure 48, representing the shallow pool above Station 1P. It should be noted also that the slope 0.0778/ft is considerably greater, for this less polluted condition, than that presented in Figure 51.

For all 28 results obtained from Dump XIV, and a line of best fit forced through the origin, the correlation coefficient for the relationship between K_{ox} and $(\Delta h/t_f)$, equation (48), is 0.995, and the slope of the line is 0.0803/ft. For the regression line with a nonzero intercept, the corresponding values are 0.995 and 0.0809/ft, respectively.

Figure 53 shows the relationship between K_{ox} and the rate of energy expenditure for values of $(\Delta h/t_f)$ less than 12.0 with all of the data averaged by main study reaches, and is

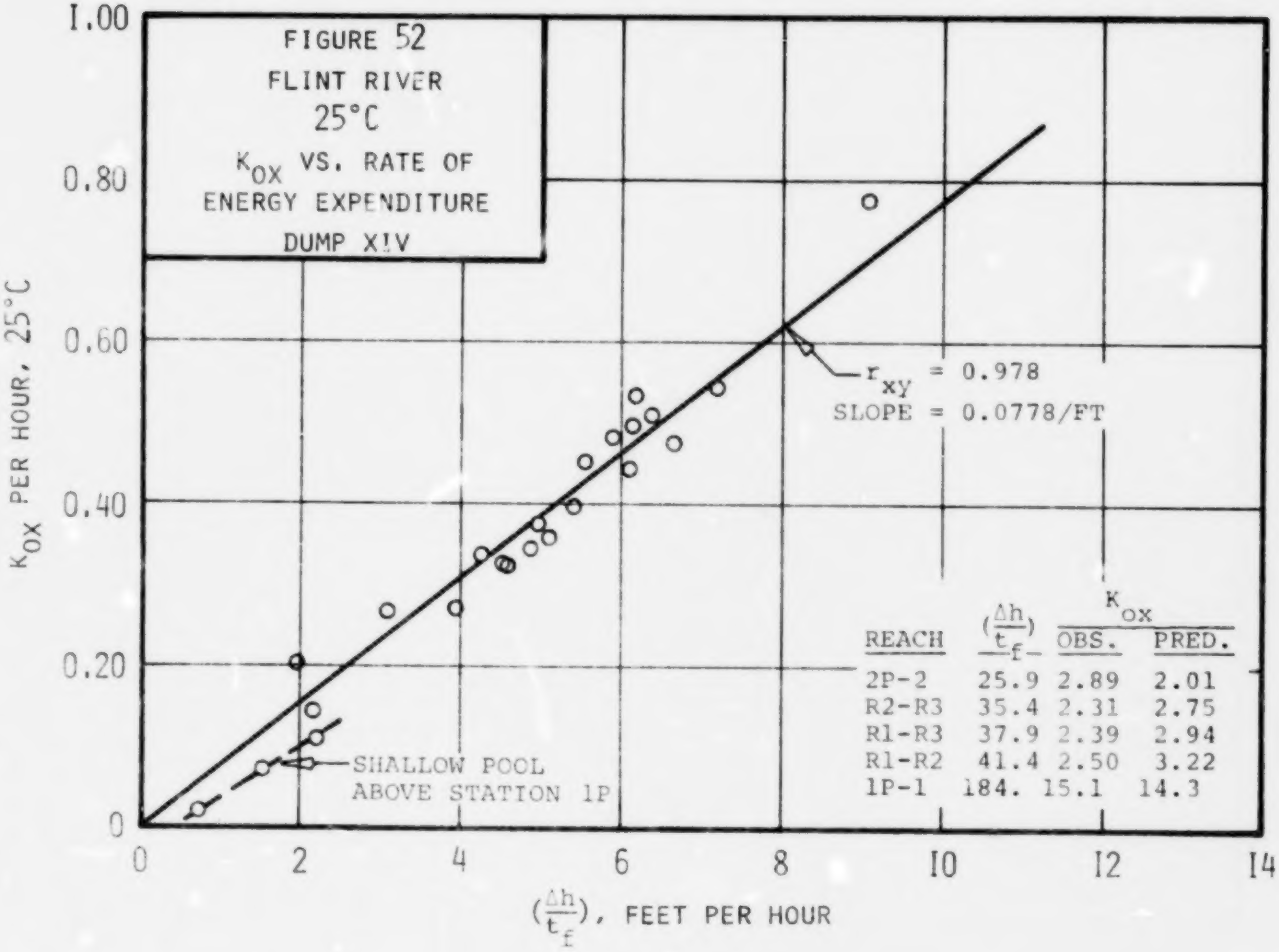


FIGURE 52
FLINT RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE
DUMP XIV

REACH	$(\frac{\Delta h}{t_f})$	K_{ox} OBS.	K_{ox} PRED.
2P-2	25.9	2.89	2.01
R2-R3	35.4	2.31	2.75
R1-R3	37.9	2.39	2.94
R1-R2	41.4	2.50	3.22
1P-1	184.	15.1	14.3

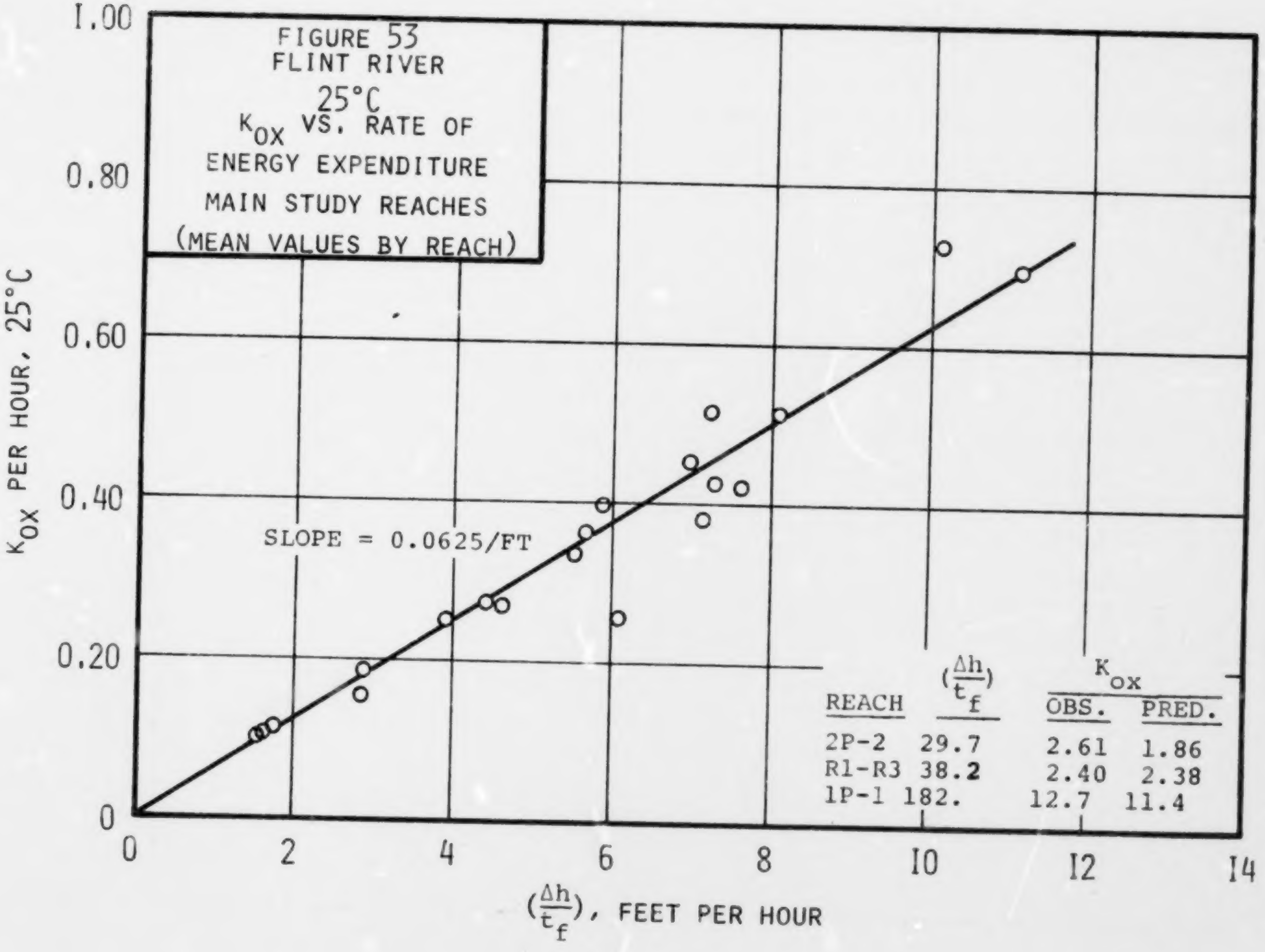


FIGURE 53
FLINT RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE
MAIN STUDY REACHES
(MEAN VALUES BY REACH)

REACH	$(\frac{\Delta h}{t_f})$	K_{ox} OBS.	K_{ox} PRED.
2P-2	29.7	2.61	1.86
R1-R3	38.2	2.40	2.38
1P-1	182.	12.7	11.4

thus comparable to Figure 51. The three study reaches having larger values of $(\Delta h/t_f)$ are again shown in tabular form to avoid scale distortion. The agreement between the observed and predicted values of K_{ox} for the first waterfall (1P-1) and for the rapids section (R1-R3) is excellent; as before, the observed K_{ox} for the second waterfall and deep pool is considerably larger than the predicted result, the predicted result being only 71 percent of the observed value. The slope of the fitted line, 0.0625/ft, is quite comparable to the slope of 0.0635/ft shown in Figure 51.

The foregoing results from the Flint River studies by themselves provide clear and conclusive evidence of the validity and the fundamental nature of the energy dissipation models for reaeration capacity, equations (48), (49) and (50). As indicated by the statistical tests, the relationships involved are very strong, and the correlation coefficients are fully as high as could be expected in terms of the range of experimental error that must be anticipated in such field operations. As indicated in Section VI, the Flint contains the widest range of hydraulic features, and the most turbulent sections, of any of the rivers studied, and, therefore, the widest range of observed reaeration results. Under these circumstances, the foregoing results and statistical tests provide ample support of the energy dissipation theory.

South River. As reported earlier in Section VI of this report, the South River was the most polluted stream studied during these investigations. Four separate waste treatment facilities discharge into the South within the tracer study section. The two larger plants, the South River STP and the Intrenchment Creek STP, each with a usual effluent flow of about 14 mgd, release their effluents just above Station A and below Station B, respectively. The Shoal Creek STP usually releases about 3 mgd just below Station F, and the Snapfinger Creek STP usual effluent flow of about 2.5 mgd is released in the immediate vicinity of Station H.

In addition to this multiple loading pattern, the records of the Georgia Water Quality Control Board (WQCB) show that during the 1969 tracer study period the South River STP bypassed substantial quantities of sewage flow directly to the South River several times; the Intrenchment Creek STP bypassed only a small part of its flow for brief periods during Dumps VIII and IX; the Shoal Creek STP bypassed about half of its flow fairly frequently during the tracer study period while flooding filters; there are no records of bypasses at the Snapfinger Creek STP.

The Georgia WQCB records also show, from occasional samples taken during the tracer study period, that the 5-day BOD of the South River STP effluent ranged from 20 to 43 mg/l (6 observations); the Intrenchment Creek STP effluent had a 5-day BOD of 26 to 48 mg/l (3 observations); the 5-day BOD of the Shoal Creek STP effluent ranged from 13 to 16 mg/l (3 observations); the effluent from the Snapfinger Creek STP contained 15 and 37 mg/l of 5-day BOD on two observations.

Initial analysis of the gas transfer data obtained in the South River tracer studies of reaeration indicated that there were marked differences in reaeration capacity from one dump to another and from one section to another, even though the results from each individual dump were consistent among themselves. For example, as noted earlier in Section VI, Dumps VI and X covered the same section of stream (Stations A to F), and both dumps took place at the same river flow and temperature. Yet the reaeration results (K_{OX}) were consistently lower in Dump X than in Dump VI. Also, the initial analysis showed that gas loss in the upper reaches (above Station G or H) tended to be consistently lower per foot of elevation change than in the lower reaches, even though the semilog plot of gas remaining vs. Δh appeared to be good for the data from each individual dump. Accordingly, the records of the Georgia WQCB were examined, as noted above, and the available results of analysis of river samples for 5-day BOD were also studied.

The foregoing analysis of the pollution situation during each tracer dump indicated clearly that for reasonable consistency as regarded the degree of pollution the South River tracer study results had to be broken down into three groups. The first and largest group of results is that for the lower study reaches--all reaches below Station H; these reaches are the farthest removed from the two larger waste treatment plants (South River and Intrenchment Creek), and the available records showed relatively low river BOD's (6.0 to 10.0 mg/l, 5-day). Thus, the lower study reach reflects the lowest degree of pollution. The second data group is that for the upper study reaches--all reaches above Station H. This group, representing the reaches just below the two larger waste treatment plants, reflects a somewhat higher usual degree of pollution, with river 5-day BOD's in the range 10 or 12 to 15 or 18 mg/l. A third group of results also stands out, consisting of all of the results for Dumps VIII and X. This group is associated with the highest degree of pollution, namely river 5-day BOD's of 20 to 30 mg/l. Specifically, Dump X was associated with river 5-day BOD's of 20 and 31 mg/l at Panola Shoals. No river BOD's are available for the exact date of Dump VIII, but the Georgia WQCB records show that on the preceeding day a large bypass (almost 7 hours long) occurred at the South River STP; Dump VIII was made at Station J, some 18 hours time of flow below the South River STP, hence was directly affected. In addition, a smaller bypass occurred at the Intrenchment Creek STP.

The following figures illustrate the observed results for the South River tracer studies, and the effects of the degree of pollution associated with each release. In reviewing all of the data contained in Appendix AIV, it was also concluded that the results for Station K in Dumps IX and XI should be rejected because of the very small amounts of krypton-85 remaining--even though the counting results appeared initially to be acceptably consistent, the actual counts were not greatly above the background count rate. It is also noted that, referring to Table 6 in Section VI, these releases contained the lowest quantities of tracer gas initially.

Although single graphs containing all of the 87 observed results from the South River studies are not provided here, statistical testing was conducted. Referring to equation (49), which relates the logarithm of the percent gas remaining to the amount of energy expended, Δh, a correlation coefficient of 0.909 was obtained, indicating a strong relationship for the 87 observations; the slope obtained, C_o, was -0.0383, indicating a half-height, $(\Delta h)_{1/2}$, of 18.1 feet for krypton. These results were for a regression line forced through the origin, and again were not significantly lower than the results for the unconstrained line of best fit.

Regarding equation (48), the model that relates K_{OX} to the rate of energy dissipation, $(\Delta h/t_f)$, the correlation coefficient found for the 87 observations was 0.971, and the slope of the regression line forced through the origin was 0.0538/ft. For the regression line with a nonzero intercept the corresponding results were 0.974 and 0.0559/ft, respectively.

The foregoing results taken alone provide quite adequate support of the energy dissipation models developed earlier. However, as noted above, the data are more suitably separated into three groups that reflect the actual conditions of pollution. When this is done, the relationships predicted by the energy dissipation models are better clarified, and the effects of pollution on the reaeration capacity of a stream become evident.

Figures 54, 55, and 56 show the relationship between percent loss of tracer gas and energy expended (Δh), as predicted by equation (50). Figure 54 represents the least polluted condition, the lower study reaches; Figure 55 reflects the usual pollution condition in the upper study reaches; Figure 56 includes those data reflecting the most polluted condition, namely, Dumps VIII and X. The strength of the relationship is obvious in each Figure. (In Figure 56, four points that involve Station J stand out; they have been ignored in fitting a smooth curve to the remainder of the observed results, for reasons that will be explained below).

It is clear from Figures 54, 55, and 56 that although the basic energy dissipation model, equation (50), provides an excellent fit of the observed results in each case, with increasing pollution there is less gas transfer. For example, for a water surface elevation change of 30 feet, under the least polluted condition (Figure 54) 75 percent gas loss occurred; with more usual levels of pollution (Figure 55) 65 percent gas loss occurred; with the heaviest pollution (Figure 56) only 54 percent gas loss occurred.

The same observed results have been replotted in Figures 57, 58 and 59 in the form required by equation (49) and to clarify the effects of pollution. Figure 57 shows the semilog plot of percent gas remaining vs. Δh for the lower study reaches. These are the same 44 observations shown earlier in Figure 54. The straight line fit of the data is excellent, and a correlation coefficient of 0.979 has been calculated for these results with the regression line forced through the origin. The slope of this regression line was $C_0 = -0.0452/\text{ft}$, and, from equation (51), the resulting half-height was $(\Delta h)_{1/2} = 15.3$ feet for krypton. From equation (53), the comparable half-height for satisfying the DO saturation deficit is 12.7 feet.

Figure 58 includes the same 23 observations shown earlier in Figure 55 for the upper study reaches of the South, and represents a more usual upstream pollution condition. As may be seen, again the fit of data by a straight line is excellent and provides powerful experimental support of the energy dissipation model, equation (49). The correlation coefficient for these results, with a regression line forced through the origin, was 0.992, and the slope was $C_0 = -0.0346/\text{ft}$. From equation (51), this leads to a half-height, $(\Delta h)_{1/2}$, of 20.0 feet for krypton, or 16.6 feet for DO saturation deficit.

Figure 59 shows a similar plot of the 20 observations associated with the heaviest pollution condition (see also

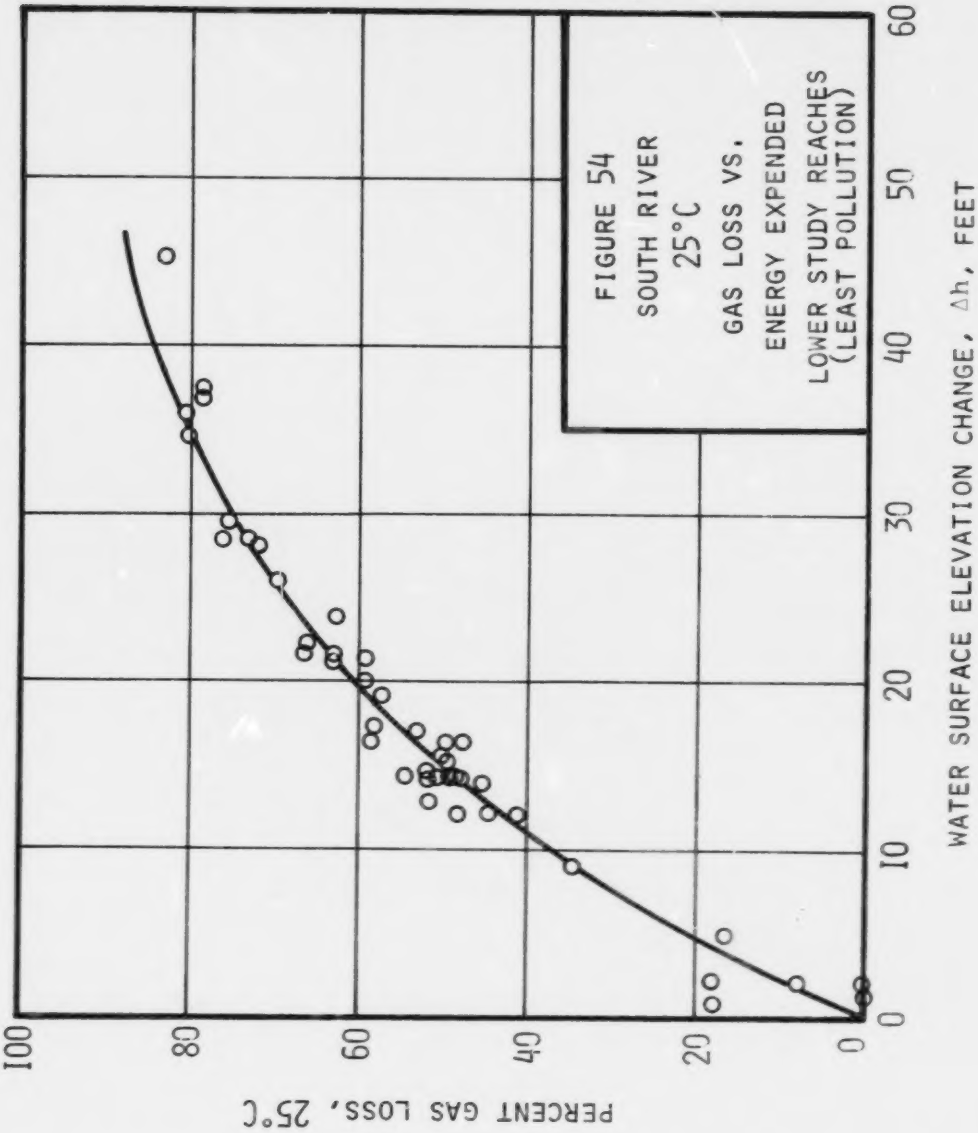


FIGURE 54
SOUTH RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
LOWER STUDY REACHES
(LEAST POLLUTION)

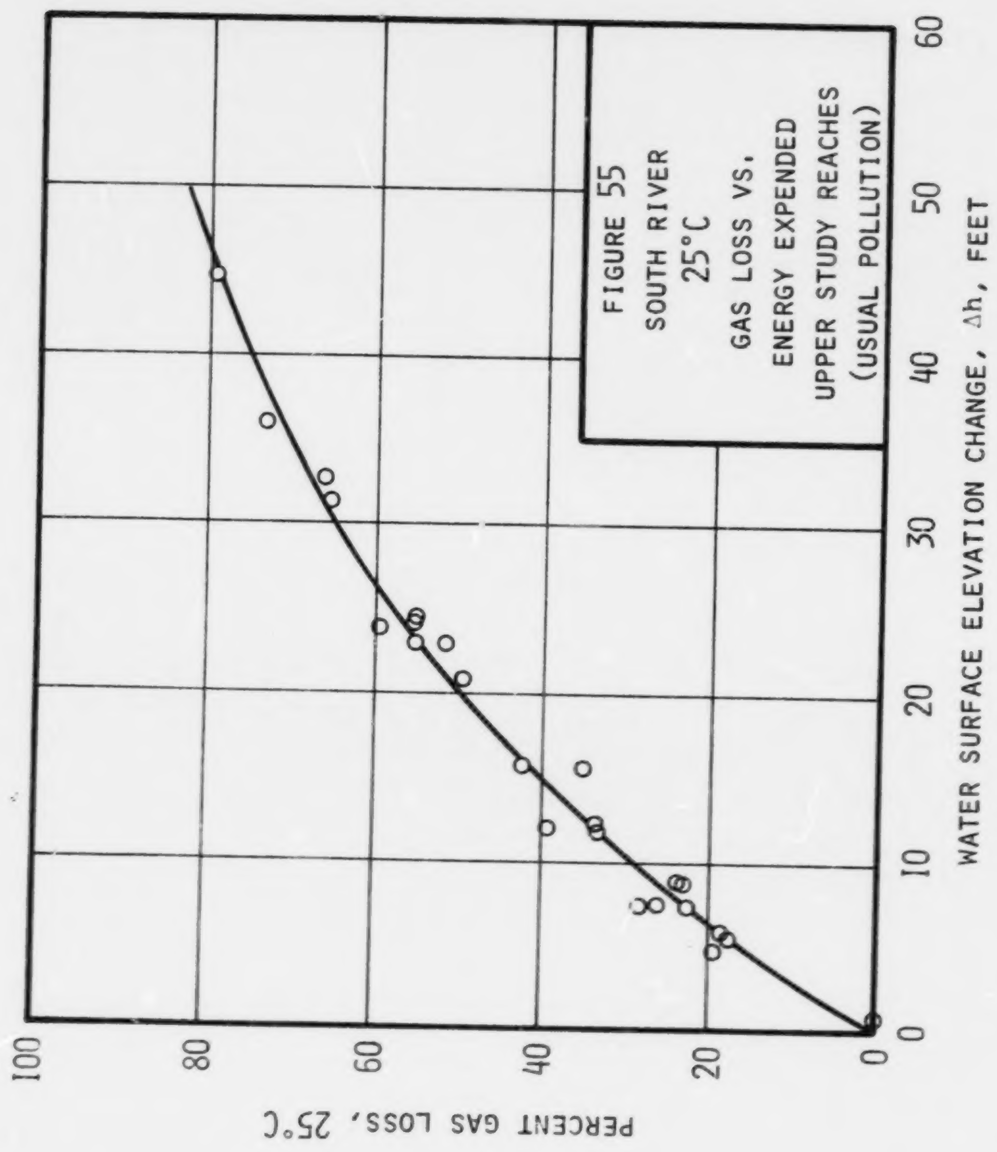


FIGURE 55
SOUTH RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
UPPER STUDY REACHES
(USUAL POLLUTION)

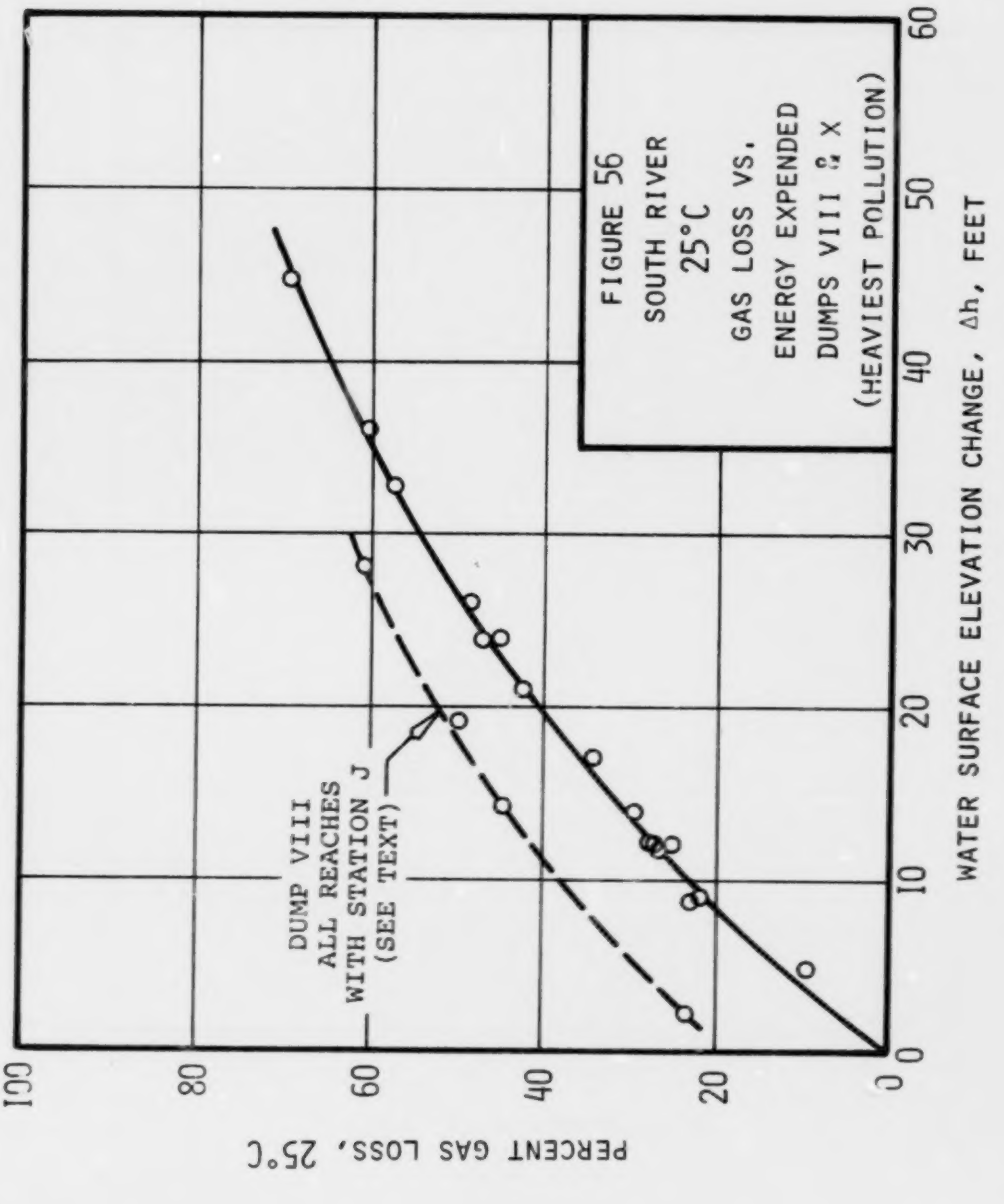


FIGURE 56
SOUTH RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
DUMPS VIII & X
(HEAVIEST POLLUTION)

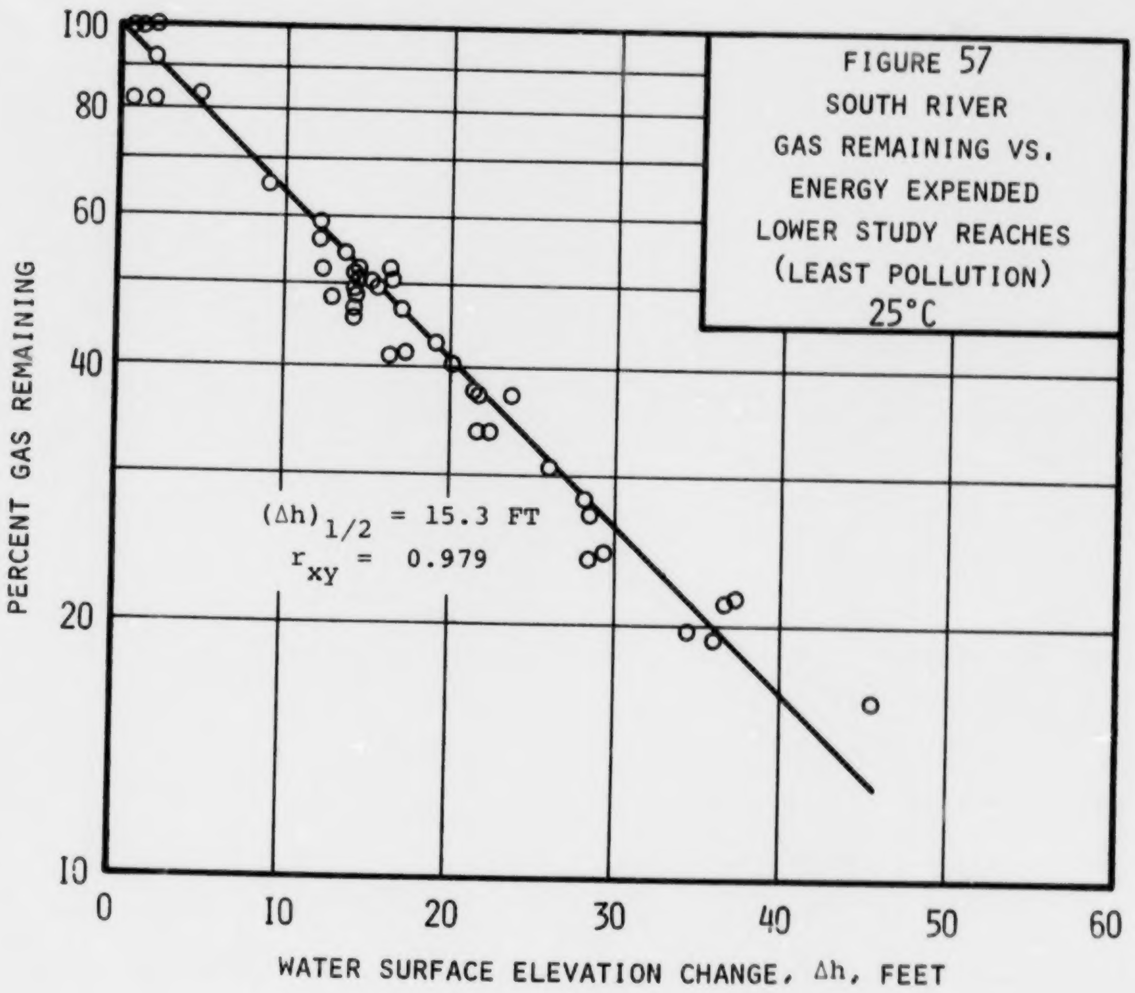


FIGURE 57
SOUTH RIVER
GAS REMAINING VS.
ENERGY EXPENDED
LOWER STUDY REACHES
(LEAST POLLUTION)
25°C

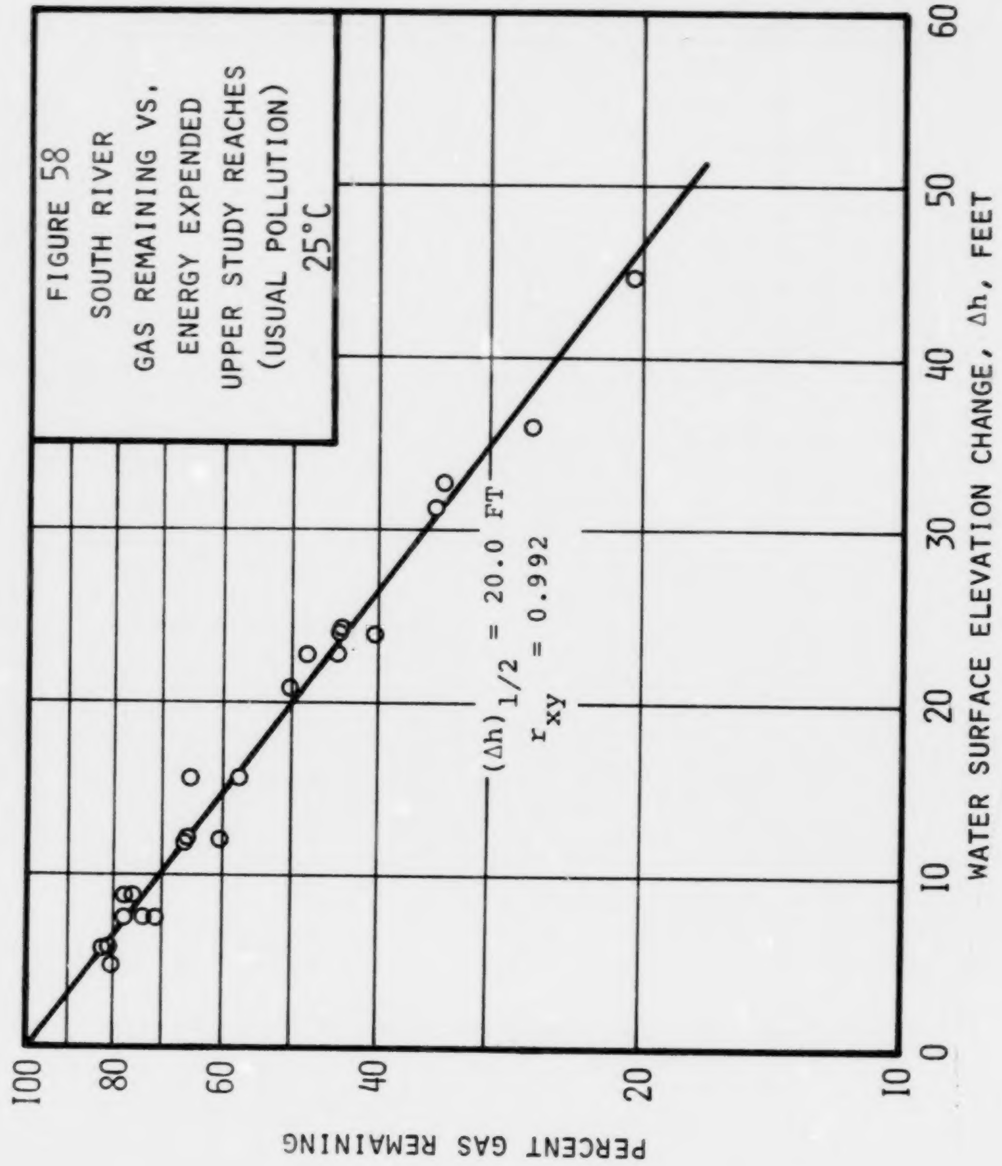


FIGURE 58
SOUTH RIVER
GAS REMAINING VS.
ENERGY EXPENDED
UPPER STUDY REACHES
(USUAL POLLUTION)
25°C

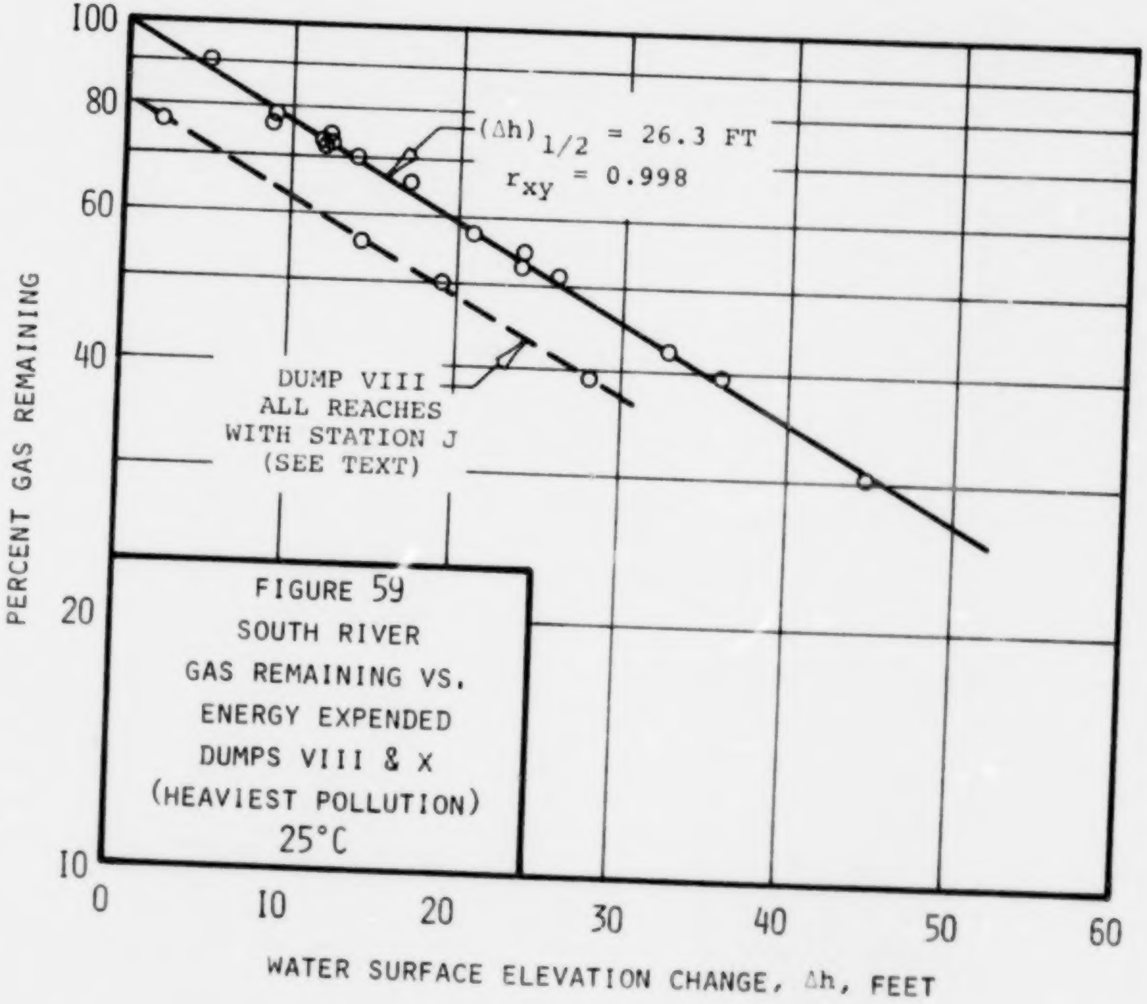


FIGURE 59
SOUTH RIVER
GAS REMAINING VS.
ENERGY EXPENDED
DUMPS VIII & X
(HEAVIEST POLLUTION)
25°C

Figure 56). Here, the discrepancy involving Station J becomes evident. The main set of data, excluding reaches that involve J, again is fitted by a straight line through the origin, and the fit is excellent. The four observations involving J have been fitted by a parallel line (dashed), but it is displaced substantially below the other. There are two possibilities regarding the cause of this discrepancy. The reach J-K includes the long deep pool above Panola Shoals, and it will be recalled (Section VI) that mixing through this pool was found to be very erratic--sometimes the flow entering the pool plunges and stays underneath the main pool volume, whereas at other times the entering flow stays at the pool surface and does not mix with the main pool volume. Hence, one possible explanation of the discrepancy shown in Figure 59 is that the flow from J stayed at the surface through the pool, resulting in greater gas loss than would have occurred if the flow had mixed fully with the pool volume.

The second possible explanation of the discrepancy involving Station J is that the dose assay was in error, and this is regarded as the most likely explanation. This source of error was discussed briefly in Section V. In the case of Dump VIII, the dose point was at Station J. Also, the specific discrepancy noted in Figure 59 did not occur in other tracer studies across these reaches. Hence, in brief, it appears most probable that in this case the discrepancy represents an error in dose assay, possibly involving loss of tracer gas during the assay procedure. The four results involving Station J have therefore been excluded from the subsequent analysis.

For the remaining 16 results shown in Figure 59, a correlation coefficient of 0.998 was obtained for a regression line forced through the origin. The slope of the line was -0.0263/ft, yielding a half-height of 26.3 feet for krypton and 21.8 feet for DO saturation deficit.

The foregoing analysis of the South River data not only provides the most powerful of support for the energy dissipation models, equations (49) and (50), but also provides considerable insight regarding the effects of pollution on gas transfer and reaeration capacity. The clearly observable decrease in the half-height for gas transfer with increased pollution shows that the reaeration capacity of a stream can be sharply reduced by the presence of untreated or partially treated domestic sewage. It should be noted in this regard also that this reduction in reaeration capacity cannot be laid exclusively at the door of the detergent LAS--the few available results obtained later, taken together with the laboratory studies referred to in Section VII, indicate strongly that observed river concentrations of LAS (in the neighborhood of 2.0 mg/l) should not cause so sharp a change in reaeration capacity.

Figures 60, 61 and 62 show the relationship between the observed values of K_{ox} (25°C) and $(\Delta h/t_f)$ for the three groups of data, as required for testirg equation (48). Figure 60 includes the 44 observations for the lower study reaches, three of these results being shown in tabular form to avoid scale distortion. As may be seen, the relationship between K_{ox} and the rate of energy expenditure is very strong and provides excellent support of the energy dissipation model, equation (48). The agreement between observed and predicted values of K_{ox} for Panola Shoals, reach K-L, as shown in the table, is excellent--the mean observed value of K_{ox} was 3.49/hour vs. a mean predicted value of 3.29/hr. For a regression line forced through the origin the correlation coefficient is 0.995, and the slope 0.0595/ft for the 44 observations. If the analysis is limited to the 41 observations having $(\Delta h/t_f)$ less than 8.0, the corresponding results are 0.949 and 0.0556/ft, as shown in Figure 60.

As may also be seen from Figure 60, the observed results are somewhat more erratic at quite low values of $(\Delta h/t_f)$, especially for values less than 1.0. No special effort was made in the South River studies to achieve the greatest possible accuracy for reaches where gas loss was likely to be very low, such as the reach J-K (the pool above Panola Shaols). As a result, for such occasional reaches the experimental error involved in laboratory analysis for tracer concentrations was somewhat larger than usual, and the observed results more erratic. For example, Figure 60 shows two values of K_{ox} to be zero (at $\Delta h/t_f = 0.65$ and 1.61); in both cases, this is because the observed gas loss was essentially zero (see also Figure 54) within the reach J-K. In later studies of the Chattahoochee River reaeration capacity, a higher degree of accuracy was obtained by counting larger numbers of samples for longer counting periods.

Figure 61 is a similar plot of the observed data for the upper study reaches, reflecting the intermediate level of pollution. Again, the relationship between K_{ox} and $(\Delta h/t_f)$ is very strong, and the results for higher values of $(\Delta h/t_f)$ shown in the table also reflect good agreement between observed and predicted values of K_{ox}. For the 17 observations having $(\Delta h/t_f)$ less than 10.0, the correlation coefficient for the line forced through the origin was 0.959, and the slope 0.0414/ft. It may be noted that, as expected, the slope has been reduced, compared to Figure 59, for the

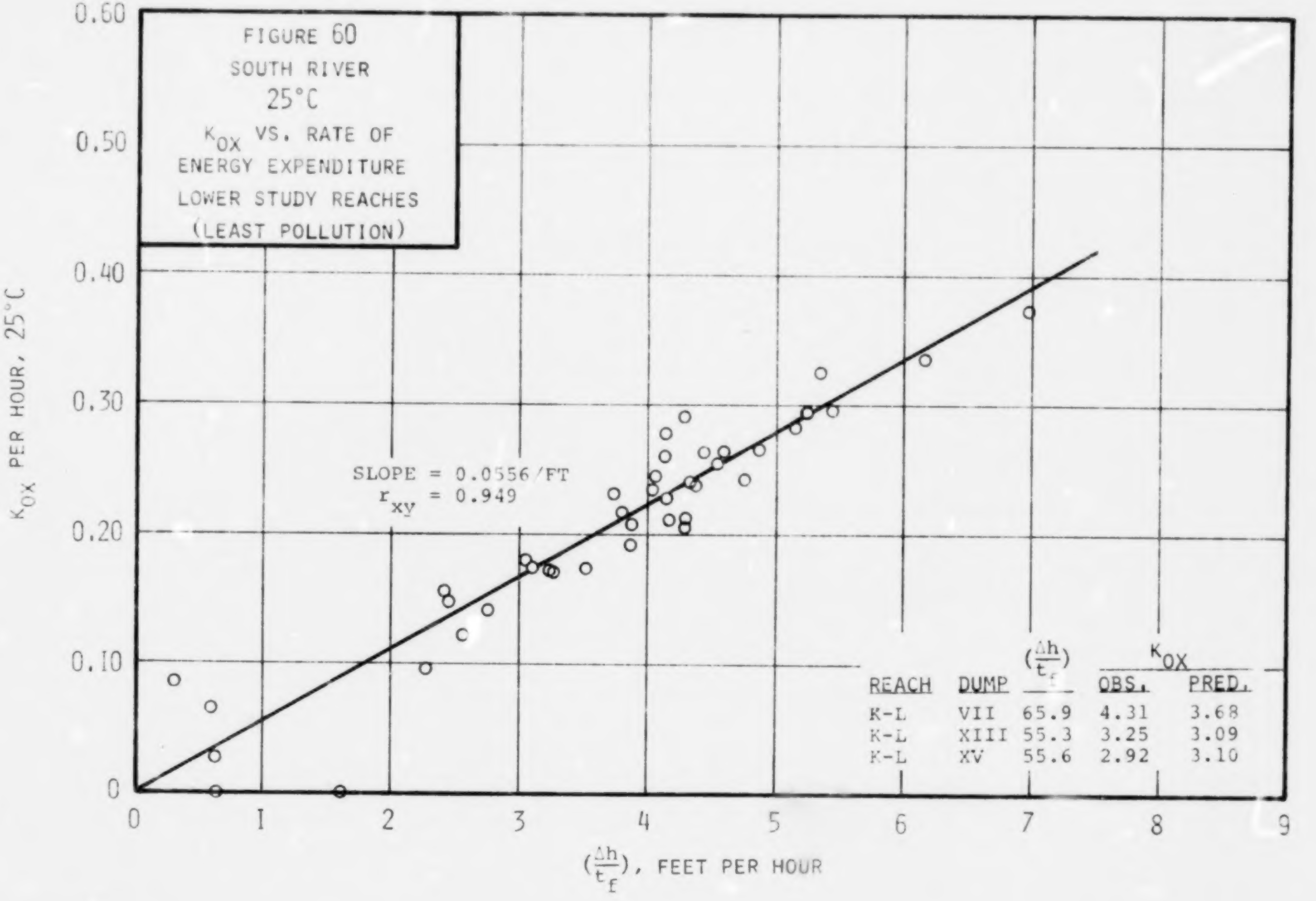


FIGURE 60
SOUTH RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE
LOWER STUDY REACHES
(LEAST POLLUTION)

			K_{OX}	
REACH	DUMP	$(\frac{\Delta h}{t_f})$	OBS.	PRED.
K-L	VII	65.9	4.31	3.68
K-L	XIII	55.3	3.25	3.09
K-L	XV	55.6	2.92	3.10

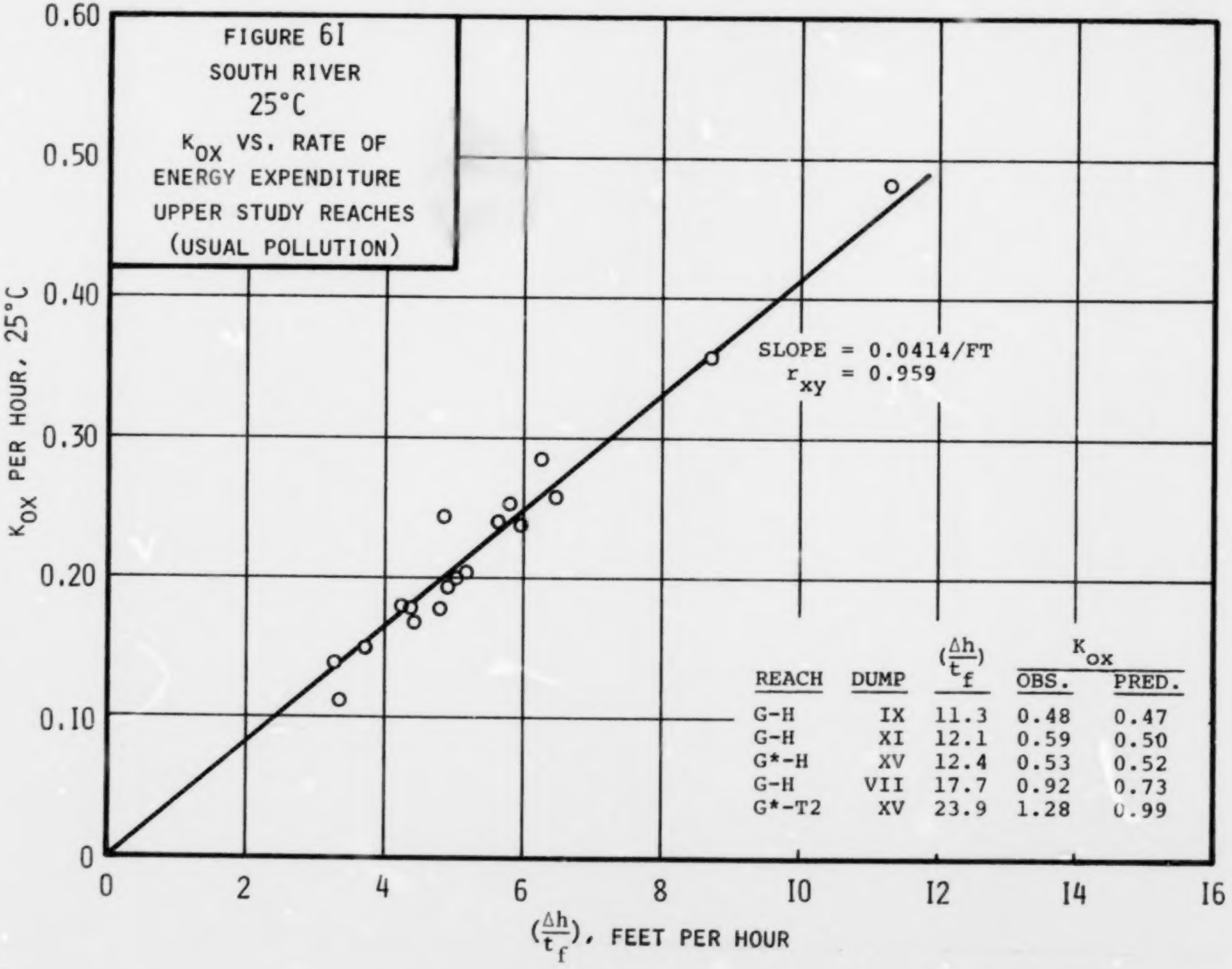


FIGURE 61
SOUTH RIVER
25°C
K_{OX} VS. RATE OF ENERGY EXPENDITURE
UPPER STUDY REACHES
(USUAL POLLUTION)

REACH	DUMP	$(\frac{\Delta h}{t_f})$	K_{ox} OBS.	K_{ox} PRED.
G-H	IX	11.3	0.48	0.47
G-H	XI	12.1	0.59	0.50
G*-H	XV	12.4	0.53	0.52
G-H	VII	17.7	0.92	0.73
G*-T2	XV	23.9	1.28	0.99

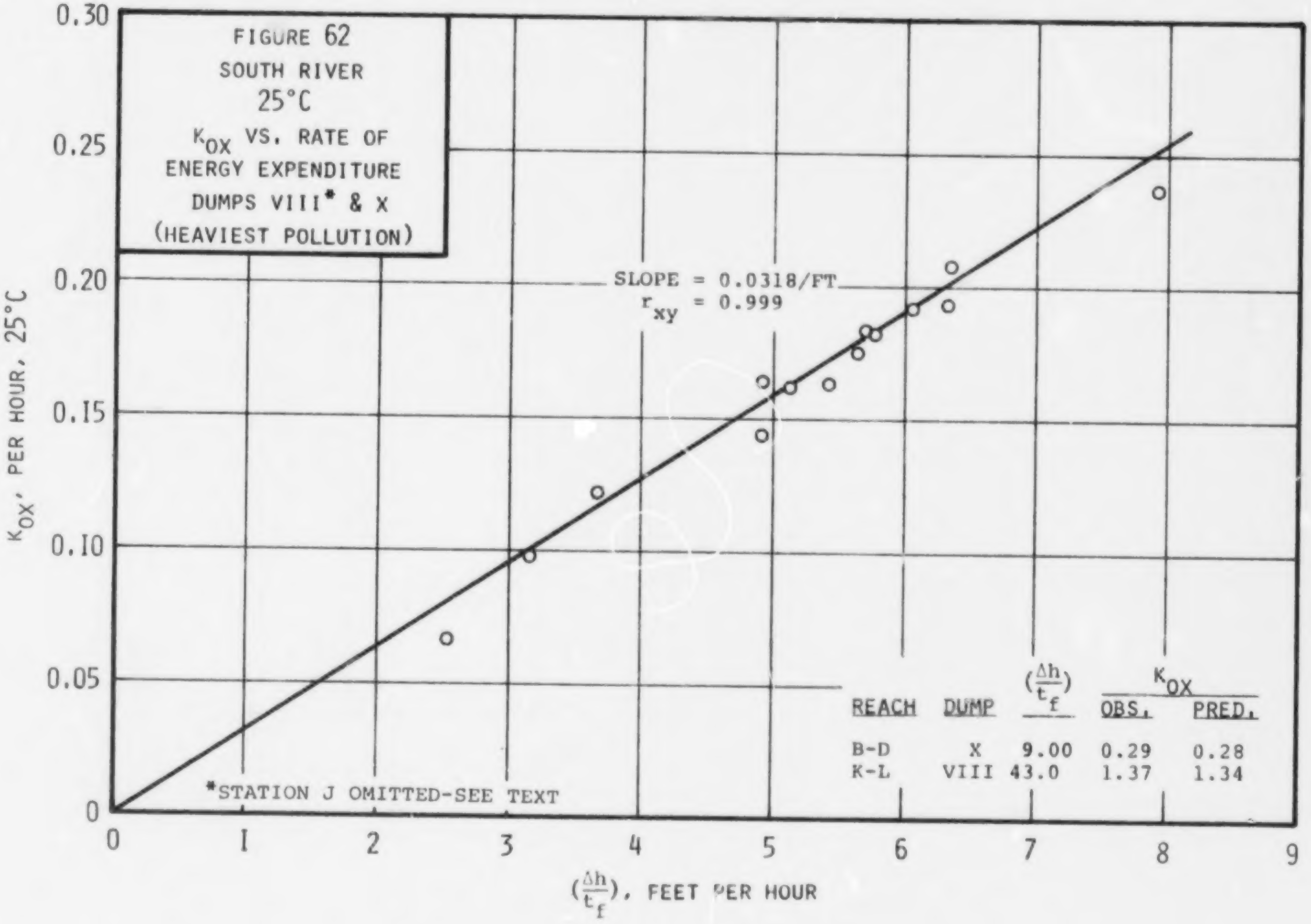


FIGURE 62
SOUTH RIVER
25°C
K_{OX} VS. RATE OF ENERGY EXPENDITURE
DUMPS VIII* & X
(HEAVIEST POLLUTION)

REACH	DUMP	$(\frac{\Delta h}{t_f})$	K_{OX} OBS.	K_{OX} PRED.
B-D	X	9.00	0.29	0.28
K-L	VIII	43.0	1.37	1.34

*STATION J OMITTED-SEE TEXT

increased level of pollution. For all results, the corresponding values were 0.983 and 0.0479/ft, respectively.

Figure 62 shows the same relationship for the 16 observed results representing the heaviest pollution condition (Station J, Dump VIII, has been deleted, as explained earlier). The correlation coefficient for the regression line forced through the origin was 0.999, and the slope 0.0318/ft. This slope reflects a further reduction in gas transfer and reaeration capacity associated with additional pollution.

The South River data thus also provide the most powerful of support of the energy dissipation models for reaeration that were developed earlier. In addition, because of the multiple pollution sources and variable pollution load in the stream, these studies have provided considerable insight regarding the actual effects of pollution on stream reaeration capacity.

Patuxent River. As indicated earlier in Section VI, the tracer studies of reaeration capacity of the Patuxent River were conducted in the early fall of 1969 for the Maryland Department of Water Resources (DWR). The gaseous tracer studies were conducted by the Georgia Tech research staff, with the exception of Dump E, whereas the Maryland DWR personnel performed the field physical studies, including measurement of stream flow, etc. The surveys of water surface elevation, cross-sectional area, etc., were conducted considerably later than the field tracer studies, and at a substantially higher flow. The available data permit adequate adjustment to average flows generally prevailing during the earlier tracer studies, but are not sufficiently detailed to allow adjustments as accurate as those that can be made for the Flint, South and Chattahoochee studies by the procedures outlined in Section V.

Also, as noted in Section VI, stream flow fluctuated substantially from one dump to the next during the Patuxent River tracer studies, and, in some cases, during the course of a single dump. As a result, the physical study data, while adequate, cannot be taken to be as accurate as those for the other stream tracer studies. This refers especially to the water surface elevation change between sampling stations during the actual tracer studies. Time of flow is measured routinely during the tracer studies, and those data are as accurate as usual, as are the gas loss results and reaeration coefficients. Although the Patuxent River studies were not a part of the research sponsored under this project, they provide additional insight into the relationships between energy dissipation and reaeration, and into the effects of pollution.

Figure 63 shows the percent loss of tracer gas corresponding to energy expenditure (Δh) for all of the Patuxent River results ($n = 30$). The observed results are somewhat more variable than in the other stream studies, but the trend of results is quite evident and fits the energy dissipation model, equation (50) very well.

The same data have been replotted in Figure 64 in the form required by equation (49), namely the logarithm of the percent tracer gas remaining vs. energy expended, Δh. As may be seen, the data describe the expected straight line very well. For a regression line forced through the origin, these results have a correlation coefficient of 0.942, indicating a very strong relationship. It should be noted also that the slope of the regression line, as represented by $(\Delta h)_{1/2}$, is steeper than the slopes found for the Flint or the South River data. The Patuxent had only one source of pollution, a highly treated domestic waste, and the $(\Delta h)_{1/2}$ of 10.5 feet for krypton clearly indicates the low degree of pollution of the Patuxent as it passes through the Wildlife Refuge. In contrast, the lowest values of $(\Delta h)_{1/2}$ observed for the Flint and South Rivers were 11.7 feet (Dump XIV, Flint River) and 15.3 feet (South River, Lower Study Reaches), and a result as high as 26.3 feet was found for the heaviest pollution (Dumps VIII and X) in the South.

In terms of overcoming an existing DO saturation deficit, use of equation (53) indicates that the Patuxent below Laurel, Maryland, has a half-height of 8.7 feet, the lowest result observed in any of these studies. Reference to Table 12, Section VI, indicates that the water surface elevation of the Patuxent falls about 7.4 feet per mile, or 8.7 feet in 1.18 miles, at low flows. Hence, under the conditions of flow and pollution load encountered during the 1969 studies, at 25°C reaeration will provide DO income to the extent of 50 percent of the prevailing DO deficit about every 1.18 miles.

BOD analyses performed by the Maryland DWR on samples taken during the reaeration tracer studies clearly showed that most of the BOD present below the Laurel STP was second stage demand, rather than carbonaceous, and that pollution levels were low. BOD time series were obtained for 12 samples collected during the survey period and represented each of the tracer study sampling stations at least once. In each case a 10-day BOD curve was developed. Only two of the 12 samples displayed a distinct first stage lasting 3 or 4 days before the onset of nitrification. The remaining 10 samples had virtually no first stage BOD, but only second stage. The 5-day BOD for all samples ranged from about

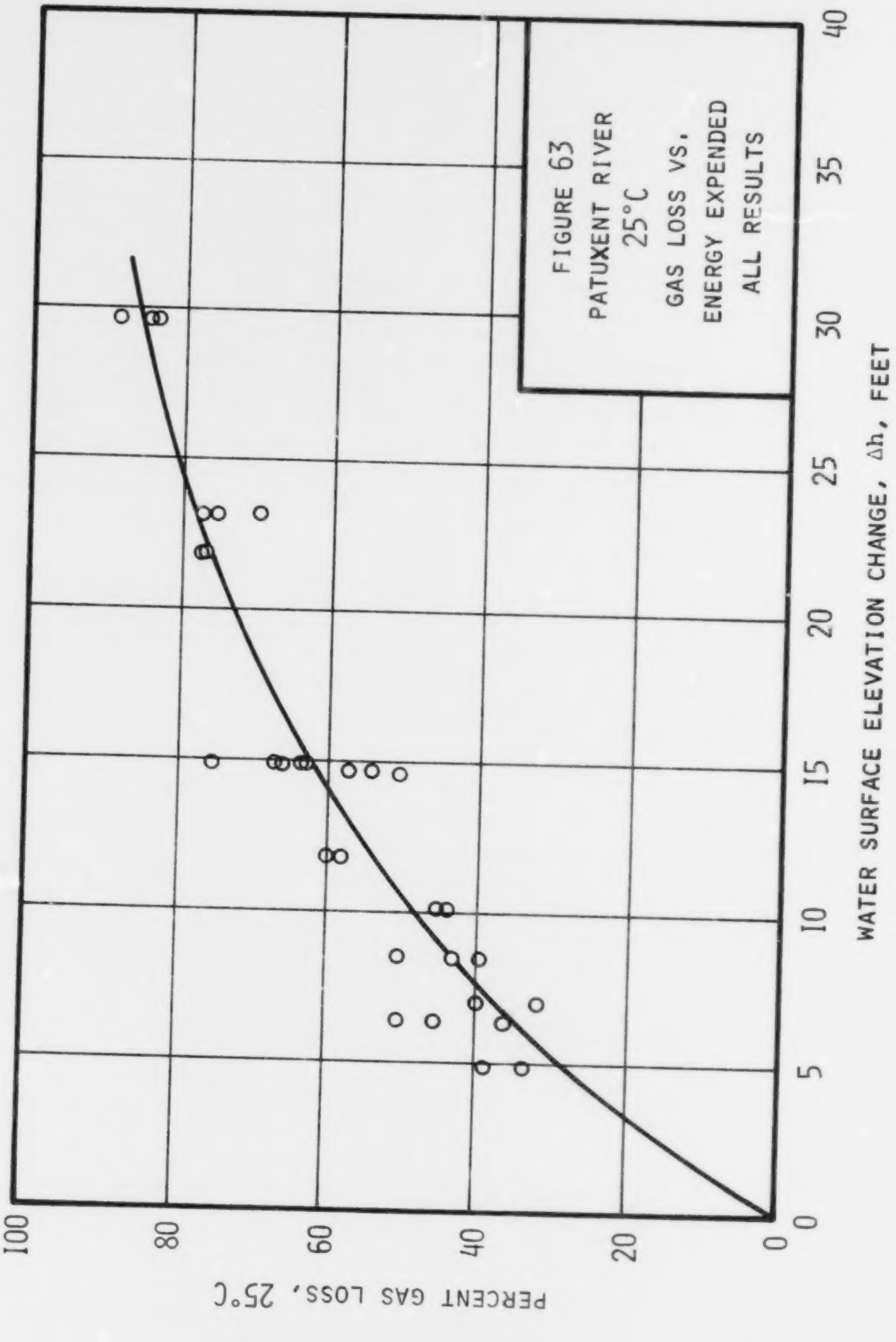


FIGURE 63
PATUXENT RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
ALL RESULTS

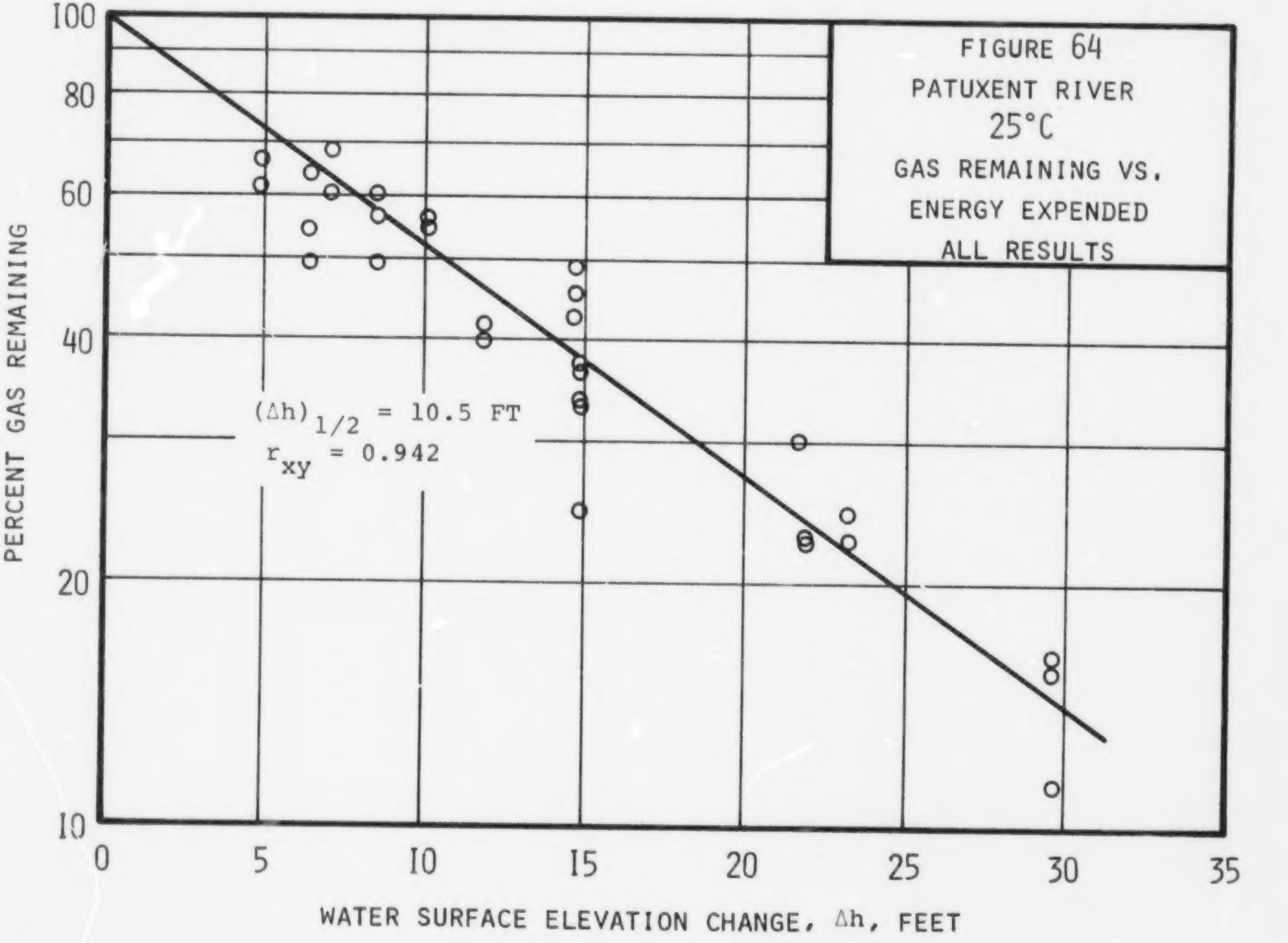


FIGURE 64
PATUXENT RIVER
25°C
GAS REMAINING VS.
ENERGY EXPENDED
ALL RESULTS

4.0 to 9.0 mg/l, and averaged 6.8 mg/l. Thus, compared to the other streams studied, the Patuxent was clearly the cleanest, and, hence, the half-height for krypton transfer was the lowest value observed in the five streams.

Figure 65 shows the plot of K_{ox} at 25°C vs. $(\Delta h/t_f)$, as required by equation (48). As may be seen, the range of observation of both K_{ox} and $(\Delta h/t_f)$ is very small, and the resulting correlation coefficient for a line forced through the origin is only 0.245. The Patuxent was characterized by a relatively high degree of hydraulic uniformity, as noted earlier, leading to such a small range of observation of K_{ox} and $(\Delta h/t_f)$ that this particular statistical test is not as meaningful as in the cases cited earlier. In essence, the range of total experimental error is relatively large in this case compared to the range of observation. For example, for the regression line with a nonzero intercept the correlation coefficient was substantially greater (0.559), the intercept was at $K_{ox} = 0.066$/hr, and the slope was only 0.0430/ft.

The theory, equation (48), requires that the regression line go through the origin, and, hence, that is the line shown in Figure 65, with the corresponding low degree of correlation. The resulting slope of 0.0804/ft is then steeper than that found for any other set of results except those for Dump XIV in the Flint (0.0803), which is just as expected as a result of the low degree of pollution.

Reference to the results provided in Section VI and Appendix AIV provides some further insight into the range of experimental error. In brief, the data show that in terms of K_{ox} and percent gas loss the observed results were satisfactorily reproducible for most reaches from one dump to another. The times of flow showed more variability, as one indication of the fluctuating river flows that occurred during the tracer studies. As indicated earlier, due to short-term fluctuations in stream flow during the tracer studies, as well as water surface elevation measurements made at another time and a considerably higher flow, the Δh values reported here are also not as stable or dependable as usual. This combination of short-term flow fluctuation and error of measurement leads to a variability of perhaps as much as 0.5 feet in any reported value of Δh; the times of flow in any reach vary by as much as 1.0 hour or more due to short-term flow changes. The net effect of such variability is still minimal as regards the results presented in Figures 63 and 64, because of the wide range of observation of percent gas transfer and Δh, and so a high correlation still results. However, the net effect on the

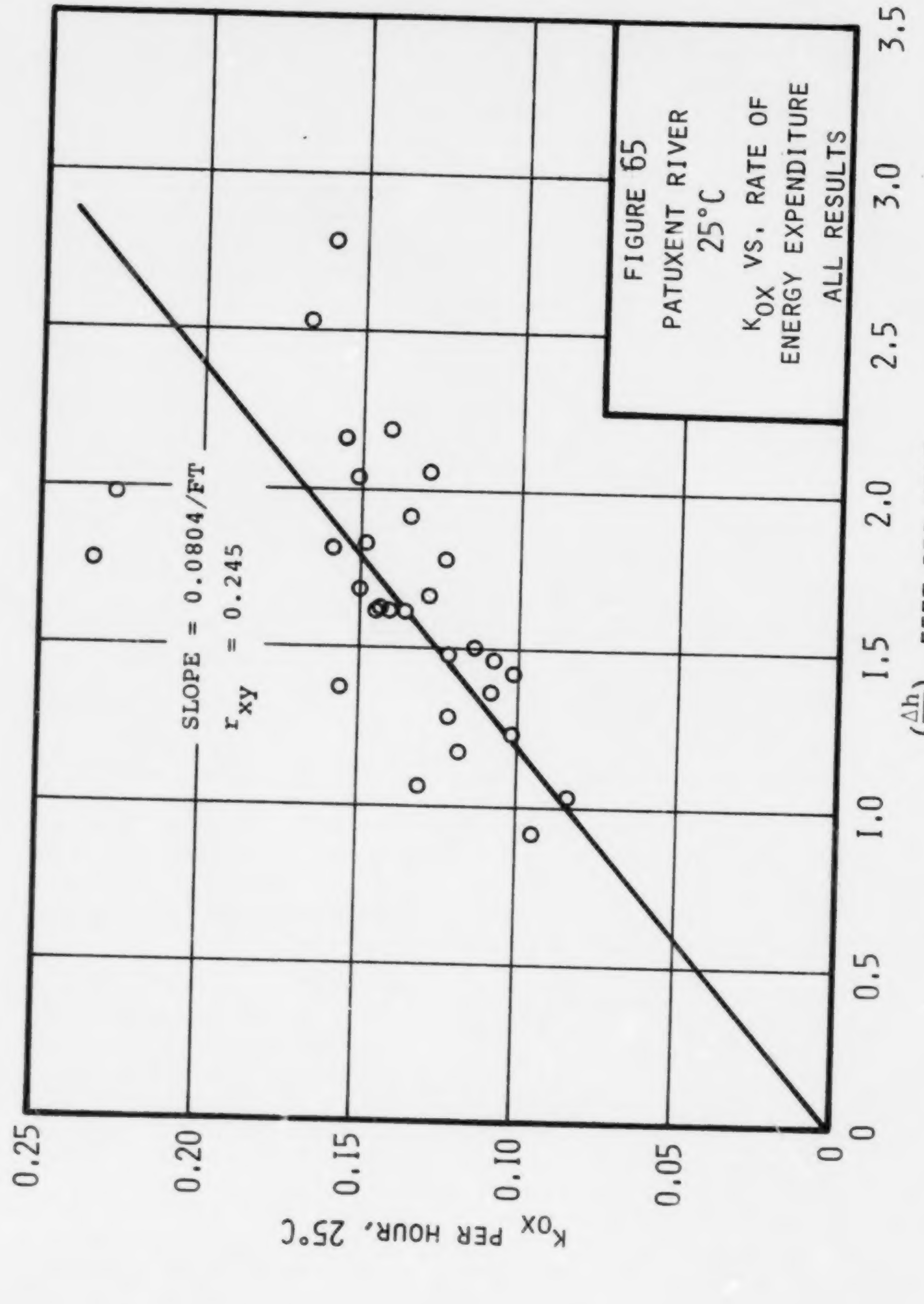


FIGURE 65
PATUXENT RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE
ALL RESULTS

small quotient ($\Delta h/t_f$) is large, and, coupled with the small range of observation of K_{ox} and ($\Delta h/t_f$), results in the low degree of correlation.

Thus, the half-height of 10.5 feet for krypton, and the associated high degree of correlation are as expected, and provide excellent support of the energy dissipation models, equations (49) and (50). The slope of 0.0804/ft obtained for equation (48) from Figure 65 is also regarded as a firm and accurate result, despite the low apparent correlation--in this case, the slope is determined on the basis of two firm points, namely, the origin and what amounts to a mean of the observed results. These results for a stream that has very little first stage BOD provide excellent additional evidence, compared to the Flint and South, of the effects of the presence (and absence) of pollution on reaeration capacity.

The results presented thus far now lead to two more general observations regarding the relationship between reaeration capacity and stream hydraulic properties. In the first place, it is clear that, of the three energy dissipation models developed earlier, the relationship between gas transfer and Δh is both simpler and more accurate and dependable than the relationship between K_{ox} and ($\Delta h/t_f$). The former, represented by equations (49) and (50) tends to minimize errors of measurement, whereas the latter, represented by equation (48), tends to magnify such errors. Thus, the degree of correlation found in tests of equation (49) is always high, whereas the combination of experimental error and a small range of observation can lead to a larger error of prediction when using equation (48). Equation (49) involves the total amount of energy expenditure, while equation (48) involves the rate of energy expenditure, and, hence, just as with any other kinetic analysis, the former is much less sensitive to errors of measurement than the latter. Thus, equation (49) is the preferred energy dissipation model for testing and subsequent application.

The results presented thus far also now lead to what appears to be a quite good estimate of the reaeration capability of a clean stream, measured in terms of the fundamental half-height for gas transfer. From these results, the range of half-heights for krypton transfer is quite small (10.5 feet in the Patuxent to 26.3 feet in the polluted South). Although no observations have been made in a stream that has never been polluted, the evidence now available indicates that a half-height less than, say, 8.0 feet for krypton transfer is quite unlikely. The matter of predicting reaeration from water surface elevation change, and application in oxygen sag computations, will be discussed in greater detail at a later point in this report.

Jackson River. The tracer studies of the reaeration capacity of the Jackson River below Covington, West Virginia, were conducted in 1966, and were not a part of this research project. As indicated in Section VI, water surface elevations were not measured during the field tracer study period, but were obtained later (1970) by others. Also, although an average flow above Covington was obtained during the tracer study period, stream flows were not measured at key locations in the study section during each individual tracer release. Thus, for these data it is not now possible to adjust water surface elevation changes to individual flows for each tracer release by the procedure outlined in Section V. Hence, the values of Δh provided in Appendix IV are not quite as accurate as those obtained for the Flint and South, and only one value of Δh is given for each stream reach.

Also, as noted in Section VI, immediately before the beginning of the tracer studies in 1966 the secondary treatment units failed at the Westvaco paper mill, and the treatment plant operated only as a primary plant during the first two tracer studies. As a result, the pollution load in the Jackson was unusually great, especially in the reaches 0-1 and 1-2, and zero DO's were observed in that vicinity.

A total of 80 observations of reaeration capacity were made during the 1966 tracer studies, and the data are provided in Appendix AIV. Figure 66 shows all of the individual results, plotted in the form required by equation (50), the energy dissipation model relating percent gas loss to water surface elevation change, Δh. As may be seen, the results describe a curve of the predicted form, and the fit of data is excellent. These same 80 results have been plotted in Figure 67 in the form required by equation (49), namely the logarithm of the percent gas remaining vs. water surface elevation change. The straight line fit of the data, as predicted by equation (49), is excellent. With a regression line forced through the origin the correlation coefficient is 0.963, as shown in Figure 67. The slope of this regression line is $C_O = -0.0444/\text{ft}$, resulting in a half-height for krypton of 15.6 ft. This is essentially identical with the results for the lower reaches of the South River.

Thus, the gas transfer results obtained in 1966, together with the water surface elevation changes obtained by others in 1970, provide strong support of the energy dissipation models, equations (49) and (50).

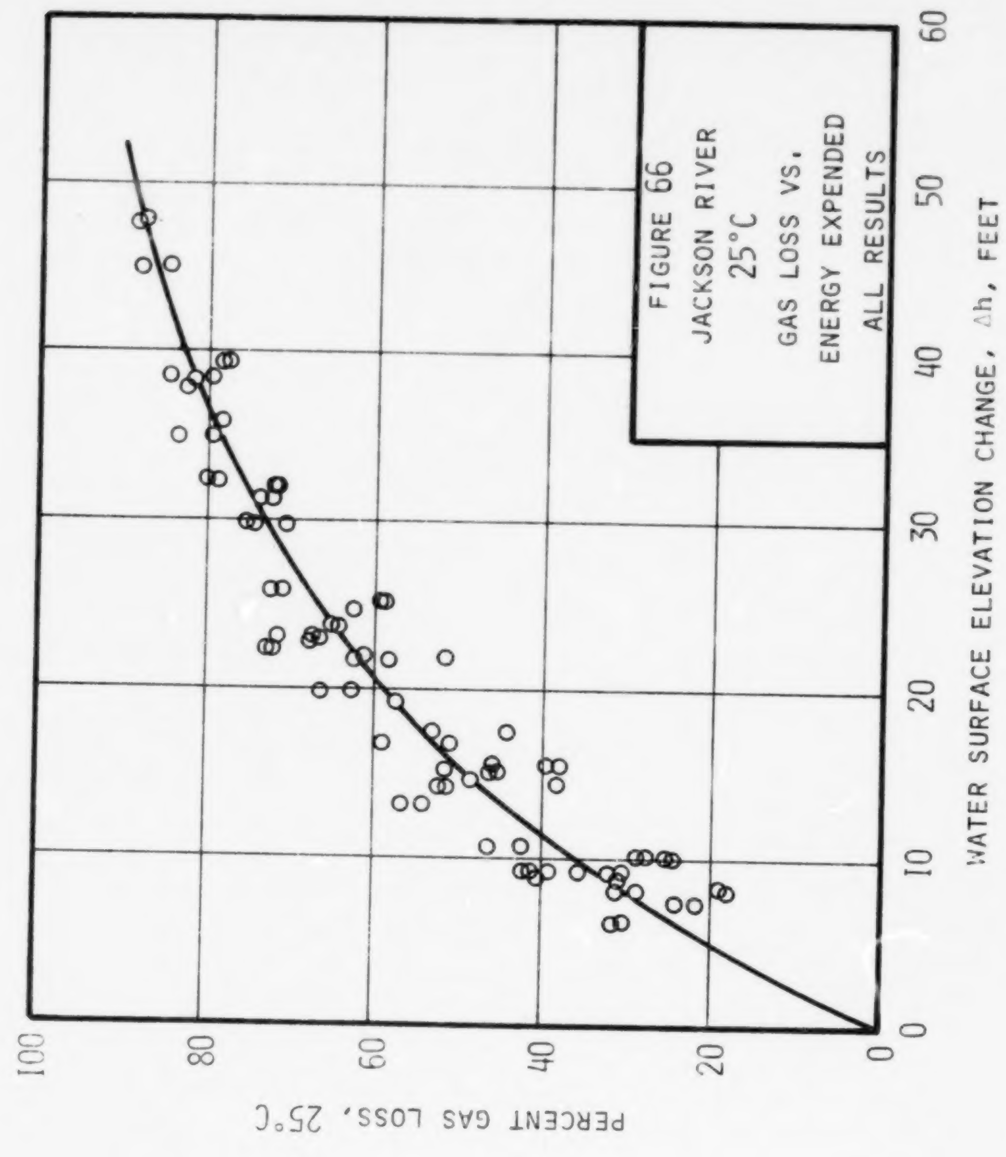


FIGURE 66
JACKSON RIVER
25°C
GAS LOSS VS.
ENERGY EXPENDED
ALL RESULTS

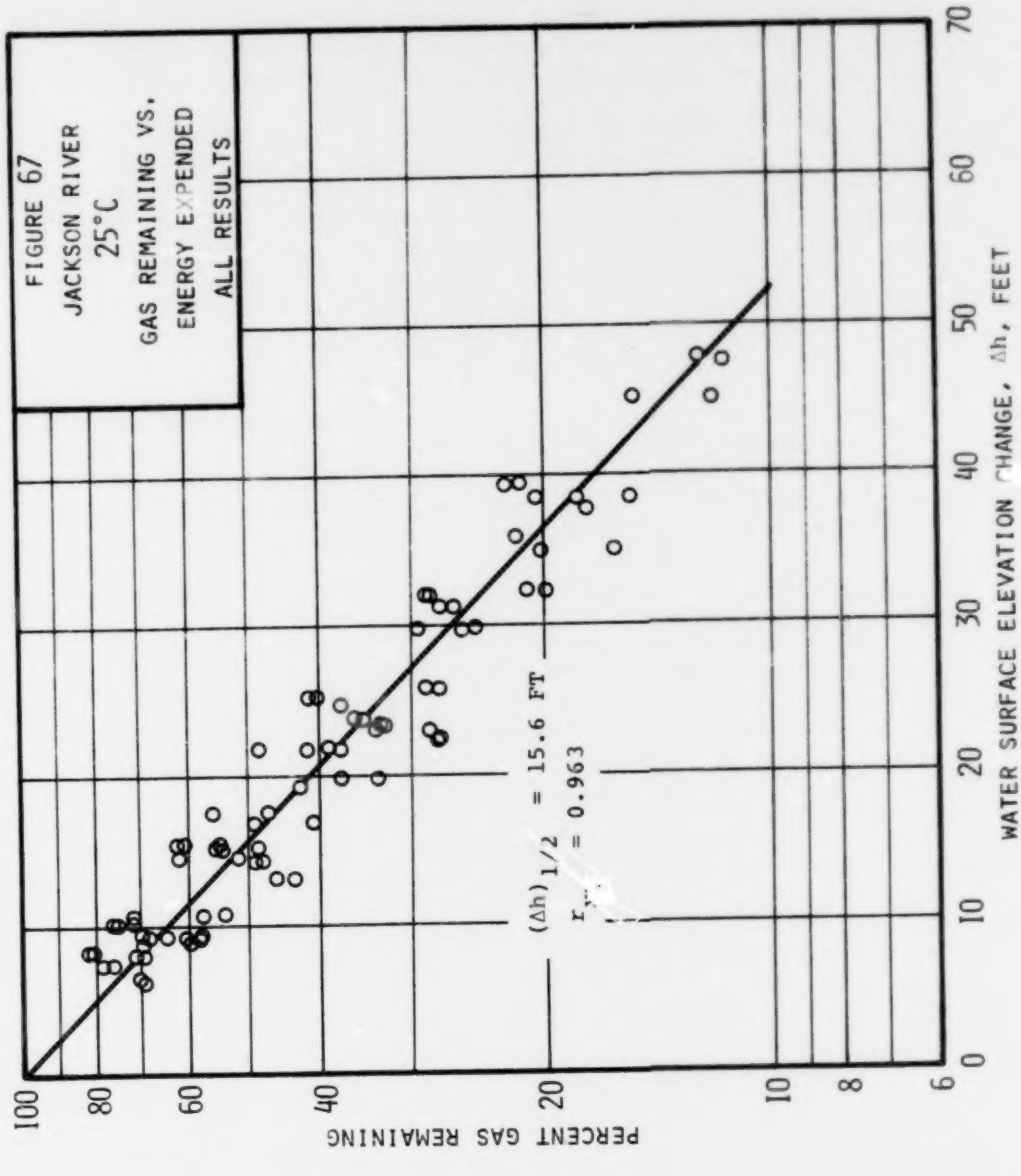


FIGURE 67
JACKSON RIVER
25°C
GAS REMAINING VS.
ENERGY EXPENDED
ALL RESULTS

Figure 68 shows the results for the Jackson River in the form required by equation (48), which is the model relating K_{ox} to the rate of energy dissipation. The range of observation is larger than for the Patuxent, but still much smaller than for the Flint or South, and as in those earlier cases, it is evident that this relationship is more sensitive to transitory flow fluctuations and errors of field measurement. Certain of the observed results have been identified in Figure 68 to illustrate this sensitivity.

Referring to Figure 68, the two results for the reach 0-1, immediately below the paper mill, have been blacked in. Quite low observed values of K_{ox} were observed, as a result of the unusual pollution situation noted above. These two results are thus regarded as reflecting a different, or separate pollution situation. Also, the five observations representing the reaches 9-10 and 10-11 have been partially blacked in for the purpose of identifying another kind of problem, and will be discussed below.

Considering all 80 observations, the correlation coefficient for the relationship shown in Figure 68 was 0.739, both for the regression line forced through the origin and for the regression line with a nonzero intercept. The slope of the line forced through the origin was 0.0533/ft.

When the two points representing the reach 0-1 are eliminated because of the unusually great pollution, for the remaining 78 results the correlation coefficient of the regression line forced through the origin is 0.811, a distinct improvement, and the slope is 0.0549/ft. The correlation might be further improved somewhat by deleting additional results (e.g., for the reach 1-2) that were certainly also affected by the large upstream pollution load, but the greatest effect is undoubtedly in the reach 0-1, and further refinement is not regarded as either necessary or desirable. The results for the 78 observations yield entirely adequate estimates of correlation and slope, and those estimates are shown in Figure 68. They provide excellent support of the energy dissipation model, equation (48), especially when it is recalled that there was a substantial time lapse (4 years) between the tracer studies and the observation of water surface elevations, that the latter were quite independently observed by others, and that refined estimates of Δh for each reach during each tracer release cannot be made.

One other source of error, or deviation, is illustrated by Figure 68. Referring to that Figure, the two partially blacked in points that are above the line of best fit represent all of the results for the reach 9-10, and the three

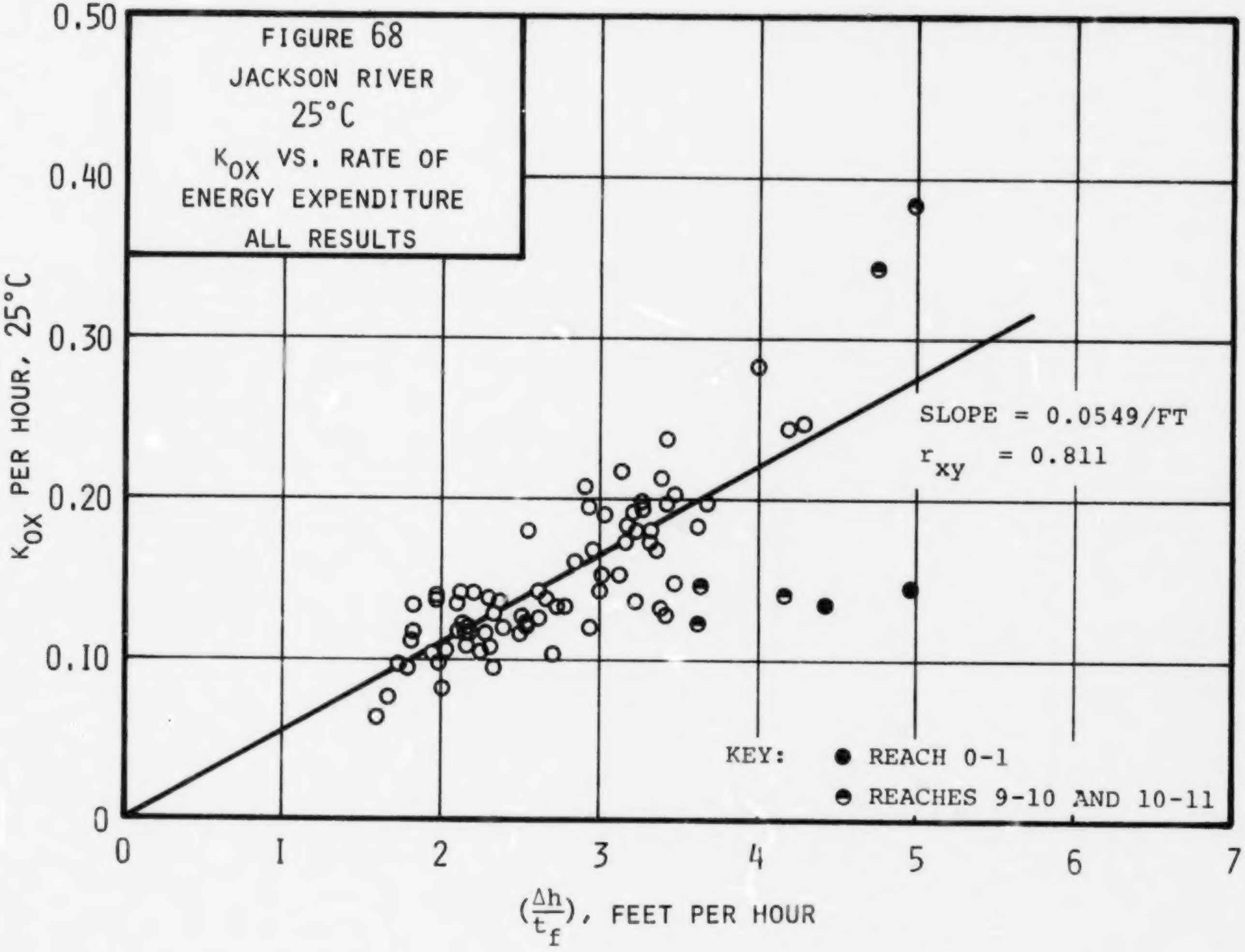


FIGURE 68
JACKSON RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE
ALL RESULTS

similar points that fall below the line are all results for the reach 10-11. During the 1970 field observation of elevation changes, considerable difficulty was encountered in finding the exact location of Station 10 from the notes of the 1966 tracer studies. Between Stations 9 and 11 considerable elevation change occurs (23.3 feet), especially in the upper portion. The exact location of Station 10 determines the amount of elevation change in each of the two segments, and, therefore, the magnitude of $(\Delta h/t_f)$ in each segment. The observed values of percent gas transfer, time of flow and K_{ox} were all quite consistent from one tracer release to the next, and the results therefore suggest strongly that the reported elevation of Station 10 is in error because of the difficulty in finding the exact station location. For example, if the Δh for the reach 9-10 were two feet larger, and the Δh for reach 10-11 were correspondingly two feet smaller, all five affected points in Figure 68 would fit the straight line much better.

As with the Patuxent, the Jackson River study section contained no unusual or remarkable hydraulic features such as dams or waterfalls or shoals or violent rapids, but consisted mainly of alternating gentle riffles and shallow pools. In that sense, the Jackson possessed a considerably higher degree of hydraulic uniformity than the Flint or South Rivers, and the range of observed values of K_{ox} (25°C) and of $(\Delta h/t_f)$ was therefore relatively small. Specifically, the range of observation of both K_{ox} (25°C) and $(\Delta h/t_f)$ was only about twice that of the Patuxent. The degree of correlation associated with equation (48), $r_{xy} = 0.811$, although still quite adequate, was thus relatively sensitive to problems such as those outlined above in connection with the reach 0-1 and Station 10. In contrast, the correlation associated with equation (49), $r_{xy} = 0.963$, is again excellent, depending only upon the amounts of total elevation change and total gas transfer, rather than upon rates.

The Jackson River studies, representing the first field tracer studies of stream reaeration capacity, thus also provide the strongest of experimental evidence supporting the energy dissipation models, equations (48), (49) and (50).

Chattahoochee River. As reported in Section VI, the tracer studies of the reaeration capacity of the Chattahoochee River were conducted in the fall of 1969 and the summer of 1970 as a part of this research. In order to obtain steady flows, it was necessary to conduct these studies on Sundays, when demands for power are low, as the river is used for the production of electric power. As a result, the degree of pollution, in terms of observed BOD's, was quite low. The

Chattahoochee studies included a total of nine tracer releases; of these, eight were conducted at a critical low flow of about 1,100 cfs in the study section, while one (the last) was at a flow of about 3,300 cfs. The observed reaeration capacity, measured in terms of K_{OX} at 25°C, was low relative to the other streams studied, being only about one-third that of the Patuxent.

A total of 37 individual observations of reaeration capacity were made in the 18-mile study section below the Clayton STP, and the detailed results are provided in Appendix AIV as well as in Section VI. Six of these observations were associated with the higher flow of 3,300 cfs, the remainder being for a steady flow of 1,100 cfs. As noted in Section VI, the BOD's were somewhat higher during the earlier studies, but were quite low in 1970, when most of the observed results were obtained. In none of the tracer studies did the BOD's approach usual magnitudes for weekday pollution loads.

The water surface elevation changes reported here were obtained and adjusted in accordance with the procedures outlined in Section V to the extent possible. As noted in Section VI, the field measurements of water surface elevation change were more difficult than usual because of the inaccessibility of the river at many locations where the banks were high and steep. Coupled with that problem, discrepancies were found among the reported elevations of the several available bench marks. The water surface elevation changes reported here were obtained by thorough analysis of all of the available bench mark information, together with the research staff level records and routine tapedowns, and are believed to be quite accurate. However, it was not possible to resolve every last discrepancy among all of the reported bench mark elevations, and hence some question must remain until such discrepancies are finally corrected by a comprehensive survey of the area. In the meanwhile, the extent of any error that might thus be incorporated in the water surface elevation changes reported here is small--at a maximum, the total water surface elevation change for the entire 18-mile study section would be increased by no more than two feet. Of course, the reaeration capacity is observed quite independently, and the values of K_{OX} are not affected.

It was pointed out in Section VI that the individual observed values of K_{OX} in certain reaches varied more, on a percentage basis, than in the studies of other rivers, although the absolute variation was not larger than usual. Increasing the number of observations of K_{OX} per reach compensated for this, and the set of mean values of K_{ox} for all reaches was quite consistent. The higher percentage variability within some reaches occurred, in essence, because the reaeration capacity of the Chattahoochee is relatively small--in any one tracer study, the total gas loss was no more than 25 percent or so, compared to 80 or 90 percent or more in the studies of other rivers. In addition, the Chattahoochee tracer doses were relatively small (mc/cfs) and velocities and dispersion were large compared to the other river studies. The following analysis of results is therefore based primarily upon the mean values of K_{ox} observed for each reach, as shown in Table 20 , Section VI. As will be seen, the statistical tests of the energy dissipation models are not satisfactory when all 37 individual results are considered, but, in contrast, yield very satisfactory results in terms of the mean values by study reaches.

Figure 69 is a plot of the data in terms of the energy dissipation model, equation (50), wherein the tracer gas loss is related to water surface elevation change. The mean values by reaches have been shown (see Table 20 , section VI), and, as may be seen, fit that model very well to the extent permitted by the range of observation. The dashed line extrapolation of the observed data has been fitted from the companion plot of results shown in Figure 70.

Figure 70 shows the mean values by reaches plotted in the form required by equation (49), namely, the logarithm of the percent tracer gas remaining vs. the water surface elevation change. As may be seen, the data describe a straight line as predicted by the theory, and the fit is excellent. For the eleven mean values, a correlation coefficient of 0.986 resulted for the line forced through the origin, and the associated slope (-0.0322/ft) yielded a half-height of 21.5 feet. These results thus provide additional powerful evidence in support of the energy dissipation models, equations (49) and (50). For the unconstrained regression line, both the correlation coefficient and the slope were essentially the same.

The 37 individual results have also been tested statistically in terms of equation (49). Considering all 37 results, regardless of differences in flow and BOD, a correlation coefficient of 0.703 resulted, and a slope of -0.0239/ft, for the unconstrained regression line. For the line forced through the origin, the correlation coefficient was reduced to 0.684 and the slope increased to -0.0284/ft. Comparing these results to those shown in Figure 70, it is evident that taking the mean values by study reach has virtually eliminated the variability of individual observations

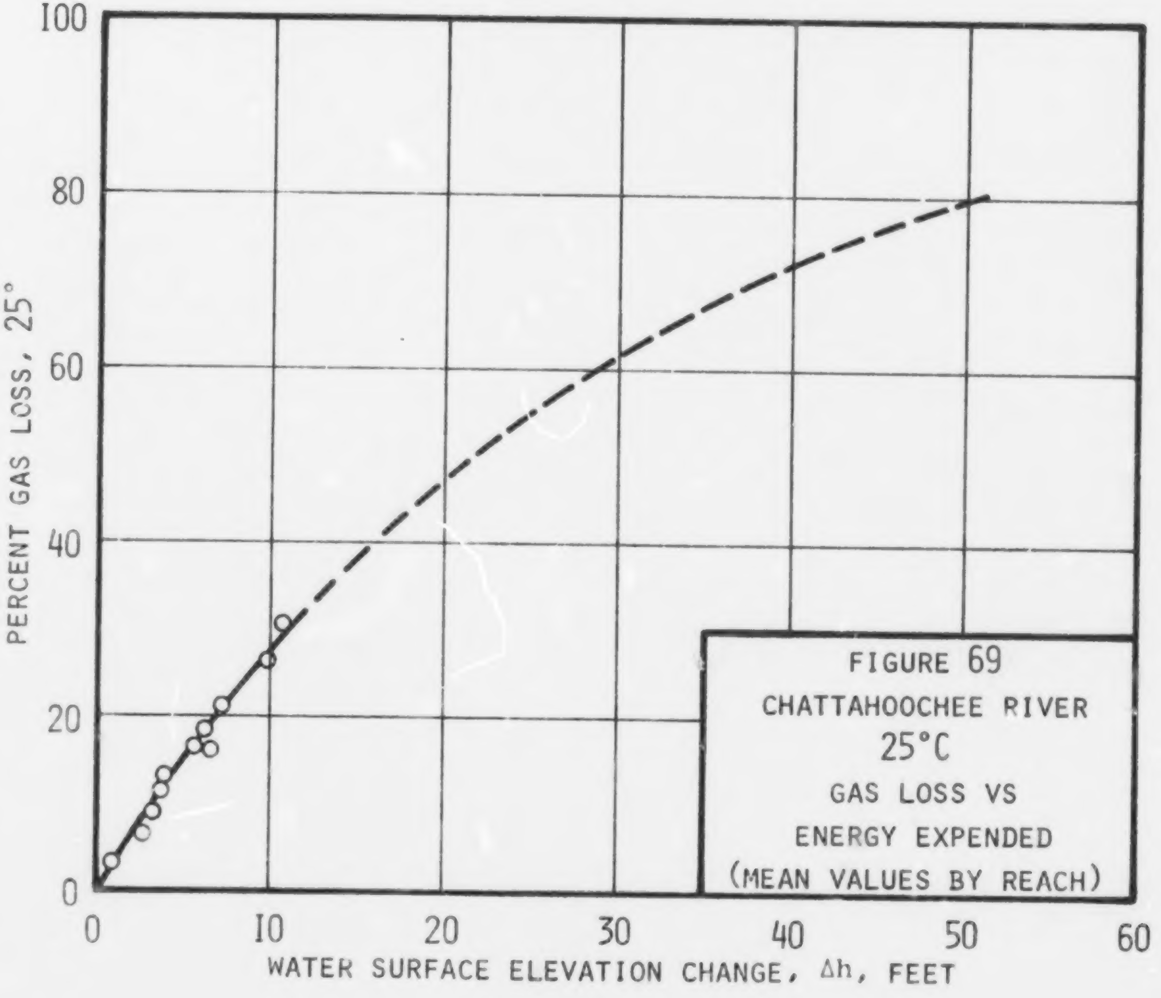


FIGURE 69
CHATTAHOOCHEE RIVER
25°C
GAS LOSS VS
ENERGY EXPENDED
(MEAN VALUES BY REACH)

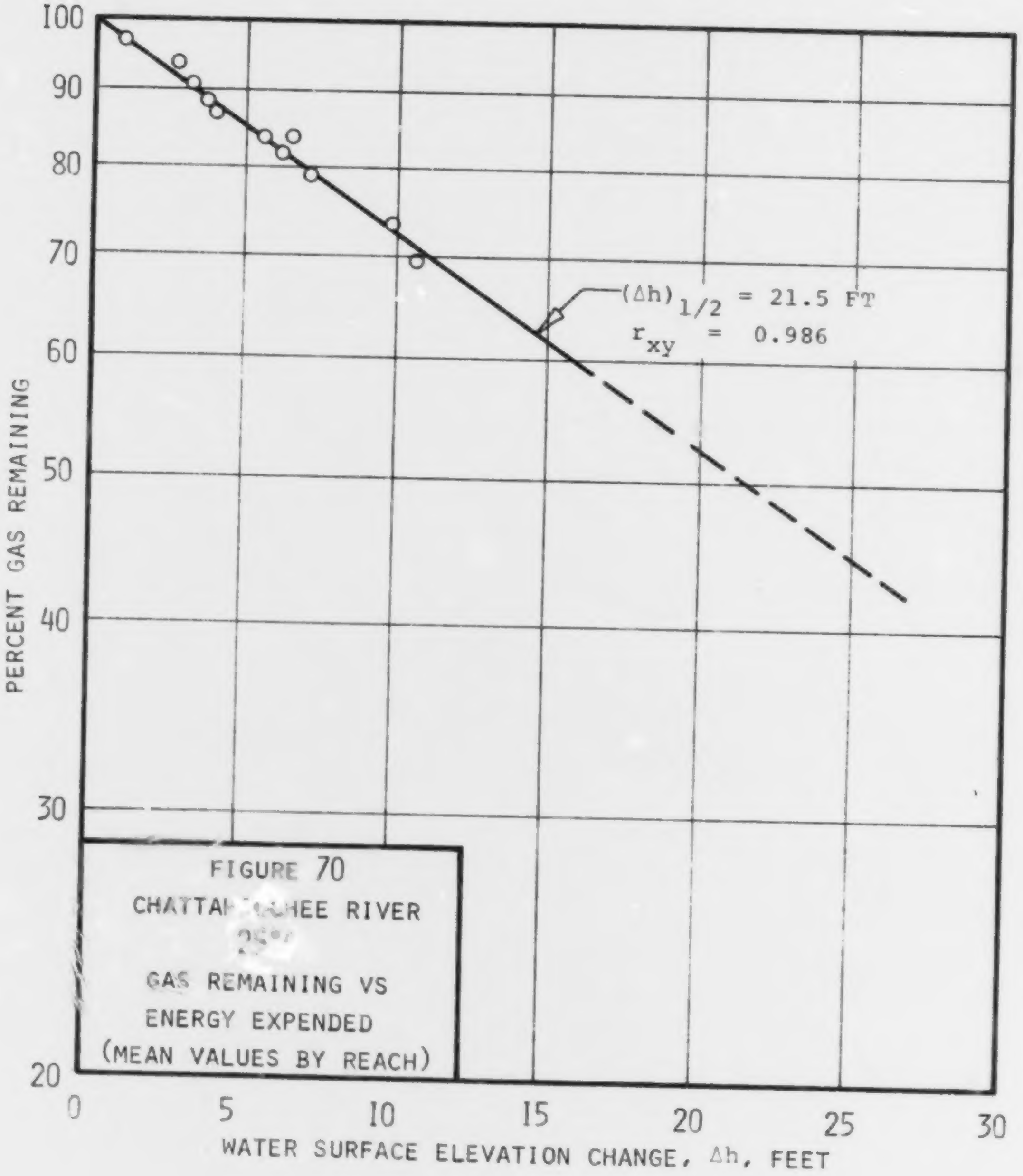


FIGURE 70
CHATTAHOOCHEE RIVER
25°C
GAS REMAINING VS
ENERGY EXPENDED
(MEAN VALUES BY REACH)

and resulted in a highly consistent fit of equation (49), in keeping with earlier comment.

Figure 71 shows the data plotted in the form required by equation (48), the energy dissipation model relating K_{OX} to the rate of energy expenditure. Although the range of observation is very small, and despite the variability of individual observations of K_{OX} within certain study reaches, the fit of the eleven mean values by study reach is excellent. For the regression line forced through the origin, a correlation coefficient of 0.927 resulted, and a slope of 0.0374/ft. For the unconstrained regression line, the correlation coefficient was 0.939 and the slope 0.0324/ft. Thus, the Chattahoochee data, taken as mean values by study reach, also provide powerful support of the energy dissipation theory in the form of equation (48).

The statistical analysis of the 37 individual observations of reaeration capacity (K_{OX}) and energy dissipation rate ($\Delta h/t_f$) leads to quite different results. As noted earlier, the small range of observation, coupled with the fact that the magnitude of the absolute error of measurement is comparable to the magnitude of K_{OX} itself, leads to poor correlation, just as these factors also affected the fit of similar data for the Patuxent. For the unconstrained regression line, a correlation coefficient of only 0.298 was calculated for the 37 individual results, with a slope of 0.0169/ft and an intercept of 0.022/hr. For a regression line forced through the origin, as required by the theory, the slope improved markedly (0.0339/ft, as compared to the 0.0374/ft shown in Figure 71), but the correlation went essentially to zero. Such results are typical where the magnitude of error or deviation is comparable to the magnitude of the observations themselves, as pointed out also earlier in connection with the statistical tests of the predictive models of O'Connor, Churchill, and others.

These particular results for the Chattahoochee River emphasize the importance of obtaining an adequate number of observations of K_{OX} for rivers where the magnitude of K_{OX} is low. In this case, the provision for four or five observations of K_{OX} in each study reach proved adequate to yield a highly consistent set of mean values, and a very satisfactory test of equation (48), even though the magnitude of K_{OX} was not much larger than the absolute error of observation.

Thus, the Chattahoochee River data also provide firm support of the energy dissipation models, equations (48) and (49), notwithstanding the several problems of measurement noted above.

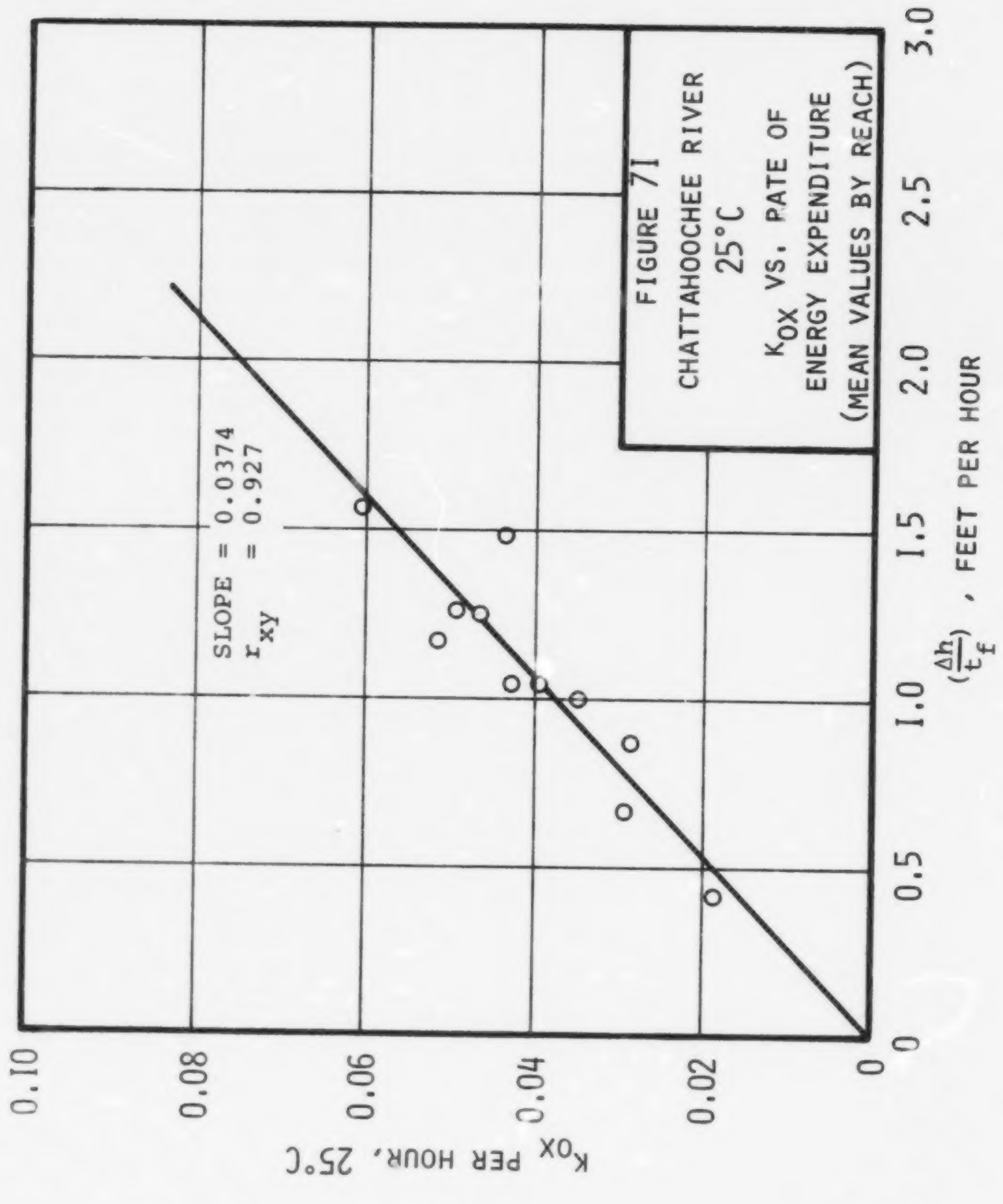


FIGURE 71
CHATTAHOOCHEE RIVER
25°C
K_{OX} VS. RATE OF
ENERGY EXPENDITURE
(MEAN VALUES BY REACH)

Before closing this discussion of the Chattahoochee River reaeration studies, it should also be noted that the half-height of 21.5 feet reported in Figure 70 does not appear to be fully consistent with the half-heights observed for the other rivers studied. The BOD's observed for river samples taken during each Chattahoochee tracer study tended to be low, at least in 1970, although 5-day BOD's in the range of 10 mg/l were found for Dumps XVI, XVII and XIX. Although the observed half-height of 21.5 feet is well within the range of observation for the four other rivers (10 feet to 26 feet), it appears to be somewhat greater than might be expected on the basis of BOD results only; if BOD as a measure of the degree of pollution were the only criterion, a half-height of about 15 feet for the Chattahoochee might be more nearly in keeping with the results for the other streams.

Of course, BOD is an indication of only one kind of pollution, and other pollutants that affect reaeration capacity may well have been present but not detected in a BOD test. Also, the Sunday pollution situation is unusual for the Chattahoochee, and it is not at all impossible that some residual effect of greater weekday pollution was still operative on Sundays--for example, cumulative contamination of the stream bed with material such as grease could quite possibly influence water surface replacement rates. Whatever the cause, the half-height of 21.5 feet is firmly established by the observed results.

Summary Analysis--Five Rivers. As a final and general test of the energy dissipation models, and of their usefulness for extrapolation to other streams, summary statistical tests of equations (48) and (49), using all of the data from the five river studies, have been performed, and the results are provided below. To recapitulate, the streams involved are the Flint, South, Patuxent, Jackson and Chattahoochee Rivers, and the reaeration tracer studies took place over a four year period, 1966-1970. The studies involved several different research staffs during that time, and took place in three separate States. They covered a total of about 70 miles of stream, in each case involving a critical section below a pollution source.

The wastes discharged to the five streams were quite varied in character and strength, and generally typical of community wastes of mixed domestic and industrial origin. They ranged from untreated or bypassed raw waste (e.g., South River) to a highly treated secondary effluent (Patuxent River), and in one stream (Jackson River) included the effluents from a large paper mill. The five-day BOD's of the river water ranged from as little as 3.0 mg/l to as much as 30 mg/l or more during individual tracer studies. Stream flows during the tracer studies ranged from as little as 5 cfs (Flint River, Dump XIV) to as much as 3,300 cfs (Chattahoochee, Dump XXV). Stream temperatures were primarily within the range 18°C to 28°C, although in one or two studies they were as low as 10°C and as high as 35°C. Thus, the data provided in Appendix AIV, and analyzed below, incorporate a quite wide range of pollution loading, flow and stream temperature. The corresponding observed values of K_2 at 25°C ranged from essentially zero in pools to a magnitude of 15.0 per hour at a waterfall.

A total of 323 individual observations of gas transfer and K_2 were made in the five rivers, the individual results being reported in Appendix AIV and Section VI. In most cases, each specific stream reach was covered by two or more tracer releases, in order to verify reproducibility and to provide mean values of K_2 for each stream reach that minimize the inevitable errors of field measurement. Reproducibility was generally excellent.

For purposes of these summary tests of all of the observed results, the mean values by stream reach have been used as representative of the best available results. These are the means reported in the individual tables of Observed Reaeration Coefficients, Section VI, and drawn from the data provided in Appendix AIV. A total of 101 mean values of K_2 are thus available, and the corresponding mean values of gas loss, Δh and $(\Delta h/t_f)$ have been obtained directly from the results given in Appendix AIV. For the sake of consistency, only those reaches having available two or more observations have been used--this has resulted mainly in deletion of those few results from special studies of the rapids sections in the Flint (reaches R1-R3) and South (reaches involving Station T2), wherein only one observation was made.

As indicated earlier, it has been necessary to delete Station 7, Flint River, because the water surface elevations at that location were not measured and are not available. Also, as outlined in the preceeding section regarding the South River studies, Station J, Dump VIII, has been eliminated because of a bad dose assay, and Station K, Dumps IX and XI, is excluded because of extremely low krypton-85 count rates.

Referring now to Equation (49), the energy dissipation model that relates the logarithm of the percent tracer gas remaining to the amount of energy expenditure, Δh, a correlation coefficient of 0.915 was obtained for the regression line forced through the origin, for the 101 available results. The slope of this line of best fit was -0.0456/ft, which corresponds to a half-height of 15.2 feet for the tracer gas. For the unconstrained regression line the correlation coefficient was the same, the slope was -0.0450/ft, and the intercept -0.0133. Elimination of the two waterfalls (Flint River, reaches 1P-1 and 2P-2) and of Panola Shoals (South River, reach K-L) changed neither the correlation coefficient nor the slope of either regression line.

Thus, the summary analysis of all of the observed results for the five rivers studied indicates that at 25°C equation (49) takes the form

$$y = \frac{C_2}{C_1} = e^{-0.0456\ \Delta h} \tag{54}$$

where y is the percent tracer gas remaining at Station 2, C_1 and C_2 are the respective concentrations of dissolved tracer gas at Stations 1 and 2, and Δh is the water surface elevation change, in feet, between stations 1 and 2. Interpreted according to equation (52), on the average for these five streams 50 percent of the tracer gas was lost to the atmosphere in every 15.2 feet of fall.

The foregoing result may be converted to DO deficit terms by use of equation (53). This leads to

$$\frac{D_2}{D_1} = e^{-0.0549\Delta h} \tag{55}$$

wherein D_1 and D_2 are the respective DO deficits at Stations 1 and 2, in mg/l, and Δh is as before. Thus, the half-height for the DO deficit is 12.6 feet, whence 50 percent of a prevailing DO deficit would be satisfied in 12.6 feet of fall, 75 percent in 25.2 feet of fall, etc., if there were no sources of concurrent DO consumption.

Statistical tests of equation (48), the model relating K_2 to the rate of energy dissipation, $(\Delta h/t_f)$, were equally satisfactory. For these tests, the two waterfalls (Flint River, reaches 1P-1 and 2P-2) and Panola Shoals (South River, reach K-L) were handled separately in order to avoid the undue statistical influence of the very high associated values of K_2 and $(\Delta h/t_f)$. Thus, the 98 results having a $(\Delta h/t_f)$ of less than 12.0 were tested first, and following that the three results associated with the waterfalls and Panola Shoals were added for the test of all 101 available results.

For the 98 results having $(\Delta h/t_f) < 12.0$, the coefficient of correlation obtained was 0.905 for the regression line forced through the origin, and the slope of the line was 0.0524/ft. For the unconstrained regression line, the correlation coefficient was identical, the slope was 0.0509/ft, and the intercept was 0.0075. Accordingly, on the average for the five rivers studied, equation (48) may be written as

$$K_2 = 0.0524 \left(\frac{\Delta h}{t_f}\right) \qquad (56)$$

where K_2 is the DO reaeration coefficient (to the base e) at 25°C, per hour, Δh is the water surface elevation change in the stream reach, in feet, and t_f is the time of flow within the reach, in hours.

Inclusion of the two waterfalls and Panola Shoals expands the scale of observation considerably and improves the correlation. However, these three additional results then appear to have an unduly great effect on the line of best fit. For example, the inclusion of Panola Shoals alone (n=99) changes the correlation coefficient to 0.98, while the slope stays much the same (0.0534/ft), for the regression line forced through the origin. Adding the results for the two waterfalls (n=101) yields an even higher correlation coefficient, but a significantly changed slope (0.0681/ft).

Rather than accept these last results, equation (56) is preferred, with its associated correlation coefficient of 0.905, as most representative of the main set of results. The values of K_2 for Panola Shoals and the two waterfalls may then be predicted from equation (56) and compared to the observed results:

Reach	$\left(\frac{\Delta h}{t_f}\right)$	K_2/hr, 25°C Observed	K_2/hr, 25°C Predicted
K-L	54.9	2.96	2.88
2P-2	29.7	2.61	1.55
1P-1	182	12.7	9.5

As may be seen, the prediction for Panola Shoals is excellent, whereas the predictions for the two waterfalls are somewhat low. As noted earlier, the reach 2P-2 includes a deep mixing pool below the waterfall, and the data indicated an associated enhancement of gas transfer; the prediction for the reach 1P-1 is better, and agrees quite well with one of the two available observed results (9.5/hr vs. 10.2 and 15.1).

The foregoing tests involving the available results for the five rivers provide ample verification and support of the energy dissipation models for stream reaeration capacity, and of their basic nature and general applicability. Those models now permit rational prediction of stream reaeration, with a degree of accuracy and dependability not heretofore possible.

PREDICTION OF STREAM REAERATION

The primary objective of this research has been to improve the ability to predict the reaeration capacity of a stream section in terms of the hydraulic properties of that section. Reaeration is a direct function of turbulent mixing in the specific sense of water surface replacement, and hence, to be successful, the predictive model must explain reaeration in terms of the hydraulic properties that cause surface replacement.

The predictive models that have been available prior to this research attempt for the most part to relate the reaeration rate coefficient, K_2, to the velocity and depth of stream flow (see Section IV). The original model of this form was proposed in 1925 by Streeter and Phelps[2], and those authors indicated clearly then that they did not regard their model as sufficiently accurate or general for widespread application. The more recent and currently available predictive models largely follow the same empirical form. They disagree among themselves, mainly regarding the magnitude of empirical coefficients. As has been seen, they have proved to be quite unsuccessful when tested against accurate observed values of K_2, especially for stream sections that are relatively turbulent.

The energy dissipation models, equations (48), (49) and (50), have been derived from simple considerations of energy expenditure in open channel flow and the kinetics of gas transfer, and their theoretical basis is thus sound and complete. They have been tested against the magnitudes of gas transfer and K_2 observed in tracer studies of the reaeration capacities of five rivers. As has been shown, in each separate case the observed data provide powerful support of the energy dissipation models. Those models have also been tested, in a summary analysis, against all of the observed data from the five rivers taken together, and these summary tests also resulted in unquestionnable verification of the models. The energy dissipation models are thus regarded as thoroughly demonstrated in both the theoretical and experimental senses. They may now therefore serve as basic models for the prediction of stream reaeration capacity.

Equations (48) and (50) may be regarded as the two basic energy dissipation models. They are quite different, yet intimately related. The one, equation (48), refers to the rate of energy dissipation, and relates that to the rate of gas transfer. The other, equation (50), refers to the amount of energy dissipated, and relates that to the amount of gas transferred. Equation (49) is merely a mirror form of equation (50), referring to the amount of gas that remains, or has not been transferred. As has been noted, amounts are easier to measure accurately than rates, as a rule, and equation (50) is therefore the simpler and more dependable form.

The Escape Coefficient. In order to use equations (48), (49) and (50) to predict stream reaeration capacity, the only term that needs to be evaluated is the exponential coefficient, c. Because of its nature, as outlined below, c is designated the "escape coefficient", and will be referred to in that manner for the remainder of this report.

Although it has been mostly ignored in the discussions presented thus far, it is now emphasized that the exponential coefficient c is common to all three models, and has the same numerical value in all three models when restricted to a single gas and a single stream. In the material presented thus far, c has been discussed primarily as a half-height for krypton in connection with equations (49) and (50), and as the slope of a line that refers to oxygen in connection with equation (48). Actually, although arrived at in different ways and by different statistical tests, these are only different manifestations of the same number, and may be expressed as the same number through use of relationships presented earlier. The following example serves to illustrate these conversions.

Referring to the observed results for the Patuxent River, as reported earlier, Figures 64 and 65 provide the required information. From the statistical analysis according to equation (49), the observed half-height for krypton was 10.5 feet (see Figure 64). This is converted to a half-height for oxygen of 8.7 feet by use of the basic $K_{kr}:K_{ox}$ ratio of 0.83, as expressed in equation (53). The latter is in turn converted to the required slope, c, by equation (52). The value of c thus derived is 0.0797/ft. This result could also have been obtained more directly from the slope of the regression line forced through the origin, which also is converted to the gas oxygen by use of the basic ratio 0.83.

Reference now to Figure 65 provides the results obtained from separate statistical testing according to equation (48), and the desired comparison. From Figure 65, for the regression line forced through the origin the slope, c, was 0.0804/ft. This is in excellent agreement with the value c = 0.0797/ft derived from equation (49). The single value, c = 0.080/ft, is thus firmly established for the Patuxent, and may be used in any of the models, equations (48), (49) and (50), for oxygen transfer predictions for that stream.

The foregoing example was chosen also to illustrate certain other matters. As indicated in the discussion of the Patuxent River results, the quality of the observed data was not regarded as quite as good as that for the other streams. This is evident, for instance, in the unusually large spread of results in Figure 64. Also, the range of observation of K_{ox} was very small, as shown in Figure 65, and this resulted in poor correlation in connection with the testing of equation (48)--the correlation coefficient was only 0.559 for the unconstrained line of best fit, and was reduced to a very poor 0.245 for the regression line forced through the origin. Nevertheless, the agreement between the separately obtained values of c, namely 0.0797/ft and 0.0804/ft, was excellent.

The reason for such excellent agreement between the two values of c is eminently clear. The energy dissipation theory requires that the regression lines go through the origin in both Figures 64 and 65. This is simply to state that if no energy is expended essentially no gas transfer will occur. (The transfer that takes place as the result solely of molecular diffusion of the gas is trivial and entirely negligible on a comparative basis). The correlation coefficient is not the most important matter here, but rather the slope. Hence, the larger correlation coefficient (0.559) was rejected in favor of the smaller (0.245) with its corresponding theoretically valid slope.

As has been shown, the correlation coefficients associated with equation (49) have been very good or excellent in all cases, and those associated with equation (48) were equally good for the Flint, South and Jackson Rivers, and for the summary analysis of results for all rivers taken together. Excellent correlation was also found for equation (48) using the mean values by reaches for the Cahttahoochee, but not for the individual values of K_{OX} because, just as with the Patuxent, the range of observation was very small, and in the case of the Chattahoochee the magnitude of K_{OX} was of the same order as the magnitude of experimental error.

Table 28 summarizes all of the values of the escape coefficient, c, found in these studies, as reported in the earlier part of Section VIII and converted to the gas oxygen as above. All results refer to 25°C, and all refer to the line

Table 28

Observed Values of the Oxygen Escape Coefficient

River	Results	Escape Coefficient,/hr, 25°C			$(\Delta h)_{1/2}$, ft
		Eq(49)	Eq(48)	Mean	
Flint	All	0.0654	0.0635	0.0645	10.8
	Dump XIV	0.0796	0.0778	0.0787	8.8
	Other[1]	0.0584	0.0583	0.0583	11.9
South	Lower Reaches	0.0545	0.0556	0.0550	12.6
	Upper Reaches	0.0417	0.0414	0.0416	16.7
	VIII and X	0.0317	0.0318	0.0318	21.8
	All	0.0461	0.0538	0.0500	13.9
Patuxent	All	0.0797	0.0804	0.0800	8.7
Jackson	All	0.0535	0.0549	0.0542	12.8
Chattahoochee	All[2]	0.0388	0.0374	0.0381	18.2
All Rivers	All[2]	0.0549	0.0524	0.0537	12.9

---

1. All results exclusive of Dump XIV
2. Mean values by reaches

of best fit through the origin as required by the theory. As may be seen, the coefficients shown for the summary analysis of data for all five rivers are the same coefficients shown in equations (55) and (56), and have the same interpretation. The last column of Table 28 shows the half-height for oxygen deficit, obtained from the mean values of c by equation (52). The half-height is a more convenient and readily understood means of expressing the magnitude of the escape coefficient and its meaning as regards the reaeration capacity.

Referring to Table 28, the agreement between the values of c obtained from separate testing of equations (48) and (49) is excellent in each case. The only disagreement worthy of mention relates to testing of the South River data all together, in which case the derived values of c (0.0461 and 0.0538) are within ± 8 percent of their mean. This disagreement is undoubtedly due to the multiple and variable pollution load situation in the South, and no such disagreement occurs when the same data are grouped according to the degree of pollution. The range of all observed values of the escape coefficient, c, will be discussed further below.

Nature and Range of the Escape Coefficient. Before proceeding to the matter of predicting stream reaeration by use of the energy dissipation models, a brief recapitulation of the nature of the escape coefficient, c, is desirable. Referring back to the derivation of equation (48), it was shown that

$$c = (a) \times (b) \tag{57}$$

where the coefficient, a, was taken from equation (4) and the coefficient, b, from equation (47). The two coefficients, a and b, are quite distinct. From its original derivation[10], the coefficient, a, refers specifically to the physical molecular properties of the diffusing gas and to the quality of the water medium. It thus refers to such properties as the diffusivity of oxygen and its molecular diameter, and to the kind and degree of pollution present, in the sense that pollutants can influence the ability of the gas to diffuse or transfer in water. The coefficient, a, thus has nothing to do with turbulence or mixing, and is not affected by those or other hydraulic properties of the water.

Referring now to equation (47) and its accompanying postulate, it is evident that the coefficient, b, refers exclusively to the hydraulic properties of the water, and has nothing to do with the inherent molecular nature of the gas. Thus, b refers to those properties associated with the rates of water surface replacement and energy expenditure. It is a mixing coefficient, and has to do with both the degree and quality of mixing. In that sense, it may be influenced by the "uniformity" or nonuniformity of flow, or by flow itself to the extent that changes in stream flow could affect the mixing regime. As has been seen, however, changes in stream flow to the extent of a factor of two or three have had no discernible effect upon K_{ox}, so that it appears unlikely that changes of stream flow within that range have much real effect in any specific stream.

Having distinguished between the two components of the escape coefficient, c, it should also be noted that the presence of a pollutant could affect both. For instance, it was shown in Section VII that LAS and mineral oil had opposite effects on the gas transfer coefficient, K_{kr}, one (LAS) depressing it and the other (oil) raising it. Those results indicate the possibility that a specific pollutant, oil for example, may affect both the ability of the gas molecules to diffuse within the water medium, or to escape from it, and the freedom with which the water surface can be replaced (by altering the surface tension, for instance). This has not been proved by the results reported here, but appears to be a definite possibility.

In the original derivation of the basic reaeration equation[10] it was shown that the net rate of gain of oxygen in reaeration may be regarded as limited by the ability of the gas molecules to escape from the water medium, and that gas transfer is controlled by both the molecular characteristics of the gas and the rate of water surface replacement. Accordingly, the coefficient c, defined as in equation (57), has been designated the "escape coefficient."

Referring now to the observed values of the escape coefficient shown in Table 28, it is at once evident that the range of results is very small. For the five streams studied, the range of c is only from 0.0317/ft to 0.0804/ft, the comparable half-heights ranging from 8.6 feet to 21.9 feet. Thus, the largest value is only 2.5 times the smaller. Referring to the mean value for c of 0.0537/ft for all rivers, all of the results for individual streams fall within the range described by the mean plus or minus 50 percent.

It has already been noted that, when all five streams are considered, the studies reported here incorporate a very wide range of stream flow (5 to 3,300 cfs), pollution load (at least 3 to 30 mg/l of 5-day BOD), river water temperature (10°C to 35°C) and reaeration capacity (K_{ox} at 25°C from zero to 15.0/hr). The derived values of the escape coefficient are therefore regarded as being representative of a great many, probably most, streams. The corresponding very small range of c thus, by itself, indicates the fundamental nature of the escape coefficient. It also indicates that the reaeration capacity of a stream should now be predictable within relatively narrow limits of error from the stream hydraulic properties.

Both the field tracer studies of reaeration capacity and the laboratory studies of the effects of pollutants on gas transfer also show clearly that the escape coefficient is markedly affected by the kind and degree of pollution present in the water. In brief, the greater the degree of pollution, the lower the escape coefficient. This was clearly shown in connection with the laboratory scale LAS studies (Section VII), and was particularly evident in the results from the South River field studies, as well as from all of the field results taken together. (It should be noted here that, although mineral oil did enhance gas transfer, rather than depress it, the quantities of oil required were large, and this is therefore not taken to be a common significant effect in streams). In essence, pollutants reduce the magnitude of the molecular coefficient, a, and thereby also reduce c. The data indicate, in fact, that the presence of pollution is a major factor, if not the principal one, involved in the observed range of the escape coefficient. This will be of great assistance in narrowing the range of predicted values of stream reaeration capacity.

Predicting Stream Reaeration. The reaeration capacity of a section of stream may now be predicted on the basis of the foregoing information. Two modes of prediction are available, as represented by equations (48) and (50), depending upon the information available. The one, equation (48), requires an estimate of the escape coefficient, c, plus the water surface elevation change and the time of flow in the stream section. The other, equation (50), does not require time of flow information.

Equations (55) and(56) provide a sound initial basis for predicting stream reaeration. They are given here again, for convenience, and a single value of c is shown, namely the mean of the two separately derived results (0.0524/ft and 0.0549/ft), as shown in Table 28.

$$\frac{D_2}{D_1} = e^{-0.0537\Delta h} \qquad (58)$$

and

$$K_2 = 0.0537 \left(\frac{\Delta h}{t_f}\right) \qquad (59)$$

where, for the stream section between locations 1 and 2: D_1 is the DO saturation deficit at the upstream location, in mg/l; D_2 is the DO saturation deficit that would occur at the downstream location if there were no sources of oxygen consumption within the reach, in mg/l; Δh is the water surface elevation change between locations 1 and 2, in feet; t_f is the time of flow between locations 1 and 2, in hours; and K_2 is the reaeration rate coefficient (K_{ox}) per hour and to the base e. Both equations apply at 25°C. For correction to other temperatures, the escape coefficient, 0.0537/ft in this case, is corrected according to the relationships given earlier in equations (9) and (10), namely

$$\frac{c(T)}{c(25)} = \frac{K_2(T)}{K_2(25)} = 1.022^{(T-25)} \qquad (60)$$

where T is the other temperature, in °Centigrade.

Specifically, according to the results presented earlier, equations (58) and (59) are regarded as capable of yielding quite good predictions of the reaeration capacity of a "typical" or "average" stream section that is moderately polluted and reasonably well mixed.

The range of values of the escape coefficient shown in Table 28 now provides the basis for modifying equations (58) and (59) to the extent warranted by specific stream conditions. Although no field tracer studies were conducted in a stream that had never been polluted, the Patuxent River was quite clean, receiving only a highly treated secondary effluent. It seems unlikely that the magnitude of c for a never-polluted stream would be much larger than the mean of 0.080/ft observed in the Patuxent studies. On the other end of the scale, the mean of c = 0.0318 ft observed for Dumps VIII and X in the South River represents a quite heavy pollution load, in the neighborhood of 30 mg/l of 5-day BOD. Depending, then, upon the actual degree of pollution, as indicated at least roughly by the BOD of the stream, the mean value c = 0.0537/ft used in equations (58) and (59) may be replaced by a more appropriate value within the range, say, 0.030/ft to 0.085/ft, for a temperature of 25°C.

Expressed as half-heights for the DO saturation deficit at 25°C, the foregoing mean value of c for a moderately polluted stream represents a half-height of about 13 feet, and the suggested range of prediction is from a half-height of about 8 feet for a never-polluted stream to 23 feet for a heavily polluted stream.

The numerical values of c suggested above are for streams that are reasonably well mixed in the longitudinal, vertical and lateral senses. When mixing is evidently poor or erratic in one direction or another, great care is necessary in predicting reaeration capacity. Such a situation is well illustrated by the experience in attempting to measure the reaeration capacity of the long, deep pool above Panola Shoals in the South River. As shown earlier, at times the entering flow proceeded through the pool at the surface, and at other times it dropped to flow through along the bottom to the pool outlet. As a result, a wide range of reaeration coefficients was observed, from zero to relatively high values, and no single value could be regarded as truly representative for the whole pool volume. In other streams extensive lateral short-circuiting occurs. In such situations it is most important to exercise judgment regarding the portion of apparent stream volume that is adequately mixed with the flow, and the value of c to assign.

The BOD is, of course, also only a general indicator of pollution, and specific kinds of industrial waste will no doubt affect the reaeration capacity in somewhat different degree. So that again, judgment is necessary in selecting the best value of the escape coefficient, c, in specific situations. Hopefully, additional research will in the future provide firm information categorizing specific wastes in terms of their effect upon the escape coefficient.

In brief, the quality and accuracy of any prediction of the reaeration capability of a stream will depend principally upon the quality and accuracy of the information available. The prediction can be no better than the information upon which it is based. If it is merely an office exercise, or sensitivity analysis, based upon crude estimates of Δh, then the prediction will be crude to the same extent. On the other hand, if the prediction can be based upon accurate field observations of Δh and time of flow, a considerably better and more accurate estimate of reaeration capacity will result. If a specific waste of unknown impact is involved, tests of the sort described in Section VII can be of great aid in refining and improving the prediction.

Thus, the predictive models provided here are not intended to serve as substitutes for accurate work. Used judiciously, and provided with accurate information, they can provide very good estimates of stream reaeration capacity. In the final analysis, however, every stream must be regarded as individual in terms of its own peculiar mixing characteristics, the character of its waste load, etc. Thus, where the economic or ecological situation requires it, there can be no substitute for direct accurate field evaluation of stream reaeration capacity by the tracer procedures that form the basis of this report.

SECTION IX

ACKNOWLEDGMENTS

The field and laboratory research studies reported here could not have been accomplished without the generous assistance and cooperation of many individuals and organizations. Those who contributed and participated in a major degree are acknowledged below. There were numerous other persons who also helped at one point or another, perhaps to lesser degree, but nevertheless in an important way at the time, and their help is neither forgotten nor does it go unappreciated.

The Georgia Tech student assistants deserve unqualified appreciation for their efforts. They gave unstintingly of their sincere interest as well as their time and hard work, and conducted themselves and their work in all ways as true professionals. Those who contributed in a major way include: L. A. Neal, D. E. Hicks, R. F. Holbrook and H. F. Reheis, all of whom were project leaders at one time or another; G. T. Smith, L. A. Kendrick, R. W. Reineke, W. C. Carr, T. E. Hopkins, K. J. Hatcher, L. C. Hicks and J. R. Rist all contributed in many ways.

Linda Porter, the Project Chemist, worked long and at times most unusual hours, was exceptionally conscientious and dependable, and displayed a great deal of understanding and forebearance at times with engineers and other circumstances.

The Georgia Water Quality Control Board provided help and encouragement throughout the course of the project. The Water Resources Division, Georgia District, of the U.S. Geological Survey was most helpful in lending the project stream gaging and other equipment at the outset and providing other aid; the Georgia Power Company was most cooperative in arranging for steady low flows for the Chattahoochee River studies; the Region IV Office of the Environmental Protection Agency (then, the Federal Water Pollution Control Administration) helped in many ways, especially at the start of the project; the Maryland Department of Water Resources was instrumental in arranging for the Patuxent River studies, and participated fully in that portion of the research.

Field research of the type reported here is difficult at best: it must be scheduled in appropriate season, the weather and stream conditions must be suitable at the right moment, a goodly number of individuals must be available on short notice, vital supplies such as tracer doses must be on hand when needed, etc. Under such circumstances, the sympathetic understanding and unhesitating assistance of

administrative officials and staff is vital, otherwise field opportunities are lost. The School of Civil Engineering administrative staff provided much vital assistance at crucial times, and, under somewhat trying circumstances at times, always managed to provide the needed help. The Procurement Office at Georgia Tech handled a great many "RUSH" requisitions, both efficiently and pleasantly. The Health Physics staff at Georgia Tech provided much assistance, some at odd hours. The Project Officer, Dr. Walter M. Sanders,III, was especially helpful throughout the course of the project, and displayed a good deal of understanding regarding the delays that finally prove to be inevitable in field operations.

Margaret Smith, of the School of Civil Engineering staff, deserves special appreciation for typing this entire report, and for carrying out that demanding task with great patience and pleasantness.

REFERENCES

1. Black, W. M., and Phelps, E. B. "The Discharge of Sewage into New York Harbor." Report made to the Board of Estimate and Apportionment, New York City (March, 1911).

2. Streeter, H. W., and Phelps, E. B. "A Study of the Pollution and Natural Purification of the Ohio River. III. Factors Concerned in the Phenomena of Oxidation and Reaeration." Public Health Bulletin No. 146, U.S. Public Health Service, Washington, D. C. (1925).

3. Velz, C. J. "Applied Stream Sanitation." John Wiley and Sons, New York, New York, 619 pp. (1970).

4. O'Connor, D. J., and Dobbins, W. E. "The Mechanism of Reaeration in Natural Streams." Journal of Sanitary Engineering Division, Proceedings of American Society of Civil Engineers, 82, No. SA6, 1115 (December, 1956).

5. Churchill, M. A., Elmore, H. L., and Buckingham, R. A. "Prediction of Stream Reaeration Rates." Journal of Sanitary Engineering Division, Proceedings of American Society of Civil Engineers, 88, No. SA4, 1 (July, 1962).

6. Krenkel, P. A., and Orlob, G. T. "Turbulent Diffusion and the Reaeration Coefficient." Journal of Sanitary Engineering Division, Proceedings of American Society of Civil Engineers, 88, No. SA2, 53 (March, 1962).

7. Thackston, E. L., and Krenkel, P. A. "Reaeration Prediction in Natural Streams." Journal of Sanitary Engineering Division, Proceedings of American Society of Civil Engineers, 95, SA1, 65 (1969).

8. Tsivoglou, E. C., O'Connell, R. L., Walter, C. M., Godsil, P. J., and Logsdon, G. S. "Tracer Measurements of Atmospheric Reaeration. I. Laboratory Studies." Journal of Water Pollution Control Federation, 37, No. 10, 1343-62 (October, 1965).

9. Tsivoglou, E. C., Cohen, J. B., Shearer, S. D., and Godsil, P. J. "Tracer Measurement of Stream Reaeration. II. Field Studies." Journal of Water Pollution Control Federation, 40, No. 2, Part 1, 285-305 (February, 1969).

10. Tsivoglou, E. C. "Tracer Measurement of Stream Reaeration." USDI, Federal Water Pollution Control Administration, Washington, D. C., 86 pp. (June, 1967); (Available US Government Printing Office, June, 1969).

11. King, D. L. "Reaeration of Streams and Reservoirs. Analysis and Bibliography." USDI, Bureau of Reclamation, Report no. REC-OCE-70-55 (December, 1970); Available National Technical Information Service, Operations Division, Springfield, Virginia, 22151.

12. "Standard Methods for the Examination of Water and Wastewater." Eleventh Edition, APHA, AWWA, WPCF (1960).

13. Isaacs, W. P., and Maag, J. A. "Investigation of the Effects of Channel Geometry and Surface Velocity on the Reaeration Rate Coefficient." Engineering Bulletin, Purdue University, Volume LIII (1969).

14. Langbein, W. B., and Durum, W. H. "The Aeration Capacity of Streams." USDI, Geological Survey, Bulletin 542 (1967).

15. Streeter, H. W., Wright, C. T., and Kehr, R. W. "Measures of Natural Oxidation in Polluted Streams. III. An Experimental Study of Atmospheric Reaeration under Stream-Flow Conditions." *Sewage Works Journal*, VIII, No. 2, 282-316 (March, 1936).

16. Owens, M., Edwards, R. W., and Gibbs, J. W. "Some Reaeration Studies in Streams." *International Journal of Air and Water Pollution*, *8*, 469-486 (1964).

17. Gameson, A. L. H., Truesdale, G. A., and Downing, A. L., "Reaeration Studies in Lakeland Beck," *Journal of Institution of Water Engineers*, Vol. 9, p. 571 (1955).

18. Krenkel, P. A., "Turbulent Diffusion and the Kinetics of Oxygen Absorption," Ph.D. Thesis, University of California (1960).

19. Al-Saffar, A. M., "Eddy Diffusion and Mass Transfer in Open-Channel Flow," Ph.D. Thesis, University of California at Berkeley (1964).

20. Daugherty, R. L., and Franzini, J. B., *Fluid Mechanics*, McGraw-Hill, New York, p. 283 (1965).

21. Cohen, J. B., Setser, J. L., Kelly, W. D., and Shearer, S. D. "Analytical Method for the Determination of $^{3}H^{85}Kr$ in Aqueous Samples." Talanta, *15*, 233 (1968).

22. Georgia Water Quality Control Board. "Water Quality Data--Atlanta Area. Chattahoochee, Flint and South Rivers, 1968 and 1969 Data." Georgia Water Quality Control Board, Atlanta, Georgia (1970).

23. Georgia Water Quality Control Board. "Upper Ocmulgee River Basin Water Quality Survey." Georgia Water Quality Control Board, Atlanta, Georgia (1971).

24. Thackston, E. L. Personal Communication (July, 1971).

SECTION XI

PUBLICATIONS AND PATENTS

Publications

1. Tsivoglou, E. C., and Wallace, J. R. "Hydraulic Properties Related to Stream Reaeration." Proceedings, Isotope Hydrology, 1970. International Atomic Energy Agency, Vienna, 509-522 (1970).

2. Tsivoglou, E. C., McClanahan, M. A., and Sanders, W. M. "Direct Tracer Measurement of the Reaeration Capacity of Streams and Estuaries." Proceedings, July 7-8, 1970, Symposium, U.S. Environmental Protection Agency Publ. No. 16050 FOR 01/72. Supt. Doc., U.S. Gov't. Pr. Office (1972).

Patents

None.

Preceding page blank

SECTION XII

APPENDICES

Page No.

AI River Sampling Locations....................265

Flint River....................266
South River....................268
Chattahoochee River....................270

AII River Discharge at Time of Tracer Studies....................271

Flint River....................272
South River....................273
Chattahoochee River....................274

AIII Measured Hydraulic Properties....................275

Flint River....................276
South River....................282
Chattahoochee River....................292

AIV Detailed Tracer Study Results and Reaeration Coefficients....................301

Flint River....................302
South River....................306
Patuxent River....................310
Jackson River....................312
Chattahoochee River....................316

Preceding page blank

APPENDIX AI

RIVER SAMPLING LOCATIONS

Preceding page blank

RIVER SAMPLING LOCATIONS

River	Station	Location
Flint	0	1500 ft. upstream from centerline of Interstate Highway 285 between sections 0 and 1.
Flint	R1	1500 ft. upstream from Terrell Mill dam, above rapids.
Flint	R2	1200 ft. upstream from Terrell Mill dam, mid-point of rapids.
Flint	R3	1000 ft. upstream from Terrell Mill dam, below rapids.
Flint	1P	5 ft. upstream from Terrell Mill dam between sections 7 and 8.
Flint	1	20 ft. downstream from center line of Terrell Mill Road bridge, 150 ft. below dam.
Flint	2P	5 ft. upstream from Lee's Mill dam between sections 22 and 23.
Flint	2	75 ft. upstream from center line of Lee's Mill Road bridge, 100 ft. below dam.
Flint	3	9600 ft. upstream from upper Riverdale Road bridge, adjacent to gravel quary between sections 30 and 31.
Flint	3*	600 ft. downstream from station 3, adjacent to gravel quarry.
Flint	BS	1 mi. upstream from Upper Riverdale Road, before swamp between sections 41 and 42.
Flint	AS	4000 ft. upstream from Upper Riverdale Road, after swamp.
Flint	F	10 ft. downstream from confluence with Mud Creek, 2400 ft. upstream from Upper Riverdale Road between sections 47 and 48.

River	Station	Location
Flint	4	50 ft. upstream from center line of Upper Riverdale Road bridge between sections 52 and 53.
Flint	5	Upstream side of Valley Hill Road between sections 70 and 71.
Flint	6	50 ft. upstream from confluence with Vester's Creek between sections 86 and 87.
Flint	7	100 ft. upstream from abandoned Bethel Church Road bridge.

River	Station	Location
South	A	100 ft. downstream from center line of Forrest Park Road bridge between stations 4 and 5.
South	B	150 ft. upstream from confluence with Intrenchment Creek between sections 24 and 25.
South	D	50 ft. upstream from center line of Bouldercrest Road bridge between sections 36 and 37.
South	E	20 ft. downstream from center line of Panthersville Road bridge between sections 59 and 60.
South	F	50 ft. upstream from confluence with Shoal Creek between sections 77 and 78.
South	G	50 ft. upstream from centerline of Flakes Mill Road bridge between sections 114 and 115.
South	G*	50 ft. downstream from Flakes Mill Road bridge, above rapids.
South	T2	1000 ft. downstream from Flakes Mill Road bridge, below rapids.
South	H	2800 ft. downstream from Flakes Mill Road bridge, above treated sewage discharge from Snapfinger Creek Facility between sections 120 and 121.
South	J	500 ft. downstream from confluence with Corn Creek between stations 140 and 141.
South	S	4600 ft. upstream from McDonough Road bridge.

River	Station	Location
South	K	75 ft. upstream from McDonough Road bridge, above shoals between stations 158 and 159.
South	L	425 ft. downstream from McDonough Road bridge, below shoals between sections 159 and 160.
South	M	9400 ft. downstream from McDonough Road bridge off Lyons Farm Road in pasture between sections 177 and 178.
South	N	Downstream side of Flat Bridge.

River	Station	Location
Chattahoochee	0	500 ft. upstream from Georgia Highway 280 at section 17.
Chattahoochee	2	7000 ft. downstream from Interstate Highway 20 near section 80.
Chattahoochee	3	12,500 ft. upstream from Georgia Highway 166 bridge, at abandoned ferry crossing between sections 124 and 125.
Chattahoochee	4	50 ft. downstream from center line of Georgia Highway 166 bridge near section 150.
Chattahoochee	5	50 ft. downstream from center line of Georgia Highway 92 bridge near section 195.
Chattahoochee	6	9000 ft. downstream from Georgia Highway 92 bridge, at Brown's Lake.

APPENDIX AII

RIVER DISCHARGE AT TIME OF TRACER STUDIES

RIVER DISCHARGE AT TIME OF TRACER STUDIES

Flint River

Dump	Station	Discharge (cfs)
I	0	10
	1	10
	2	10
II	1	9.2
	2	9.2
	3	19
	4	25
III	0	10
	1	10
	2	10
	3	22
IV	3	24
	4	24
	5	25
	6	27
V	4	21
	5	21
	6	22
	7	28
XII	4	21
	5	21
	6	22
	7	28
XIV	0	5.5
	1	5.5
	2	5.5

RIVER DISCHARGE AT TIME OF TRACER STUDIES

South River

Dump	Station	Discharge(cfs)
VI	A	48
	B	48
	D	75
	E	100
	F	107
	G	146
VII	G	123
	H	138
	J	155
	K	158
	L	158
VIII	J	186
	K	190
	L	190
	M	206
IX	E	69
	F	85
	G	90
	H	135
	J	158
	K	158
X	A	48
	B	48
	D	75
	E	100
	F	107
XI	F	100
	G	105
	H	112
	J	130
	K	130
XIII	J	110
	K	112
	L	112
	M	121
XV	G	110
	H	122
	J	140
	K	142
	L	142

RIVER DISCHARGE AT TIME OF TRACER STUDIES

Chattahoochee River

Dump	Station	Discharge (cfs)
XVI	0	1000
	2	1000
XVII	2	925
	3	950
	4	910
XIX	0	1030
	2	1080
	3	1100
XX	0	910
	2	920
	3	950
XXI	3	1200
	4	1210
	5	1170
XXII	3	1200
	4	1210
	5	1170
	6	1170
XXIII	2	1000
	3	1130
	4	1170
	5	1120
XXIV	3	1200
	4	1230
	5	1175
	6	(1175)
XXV	0	3000
	2	3000
	3	3300
	4	3300
	5	3300
	6	(3300)

APPENDIX AIII

MEASURED HYDRAULIC PROPERTIES

HYDRAULIC MEASUREMENTS

FLINT RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
0	4.94	4.33	1.14	.66	6.86
1	12.65	19.76	.64	1.38	17.24
2	10.01	7.70	1.30	.59	13.18
3	11.76	9.41	1.25	.75	12.81
4	8.38	17.46	.48	1.13	17.02
5	8.36	36.33	.23	1.07	34.37
6	8.82	41.99	.21	1.52	27.74
7	8.54	71.13	.12	1.55	46.31
8	8.47	24.91	.34	1.16	21.79
9	7.50	12.30	.61	.72	17.54
10	7.29	11.21	.65	.60	18.94
11	8.26	10.32	.80	.54	19.27
12	11.28	19.79	.57	1.15	17.50
13	7.41	8.23	.90	.50	17.55
14	7.46	6.60	1.13	.62	10.78
15	6.83	5.99	1.14	.36	16.55
16	6.31	6.44	.98	.33	19.64
17	8.27	6.51	1.27	.41	16.17
18	8.47	9.52	.89	.65	14.84
19	7.23	6.63	1.09	.40	16.53

HYDRAULIC MEASUREMENTS

FLINT RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
20	7.76	13.85	.56	.66	21.13
21	8.15	45.26	.18	1.92	24.67
22	11.05	32.50	.34	1.61	20.98
23	10.24	18.61	.55	1.74	11.20
24	7.44	13.53	.55	.96	14.48
25	7.08	7.45	.95	.56	13.51
26	14.74	14.89	.99	.58	26.10
27	14.74	12.39	1.19	.53	23.57
28	15.76	15.60	1.01	.85	18.36
29	15.63	15.79	.99	1.09	80.31
30	15.68	15.68	1.00	.95	16.61
31	11.15	8.32	1.34	.35	23.84
32	16.49	15.86	1.04	.63	25.42
33	11.58	8.21	1.41	1.26	6.94
34	14.12	12.50	1.13	1.47	8.74
35	20.43	20.43	1.00	1.56	14.85
36	20.03	32.30	.62	2.78	13.98
37	11.91	13.38	.89	1.91	7.28
38	15.96	19.70	.81	1.06	18.85
39	17.72	30.55	.58	1.70	18.78

HYDRAULIC MEASUREMENTS

FLINT RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
40	15.12	27.50	.55	1.90	14.91
41	13.47	24.50	.55	1.38	18.67
42	17.21	11.79	1.46	1.01	12.40
43	12.68	18.38	.69	2.14	8.92
44	12.96	16.83	.77	1.36	13.66
45	21.74	34.51	.63	1.75	20.83
46	20.63	33.82	.61	1.83	18.96
47	23.95	57.02	.42	2.55	23.20
48	17.14	31.74	.54	1.63	19.99
49	20.54	21.85	.94	1.53	15.76
50	20.86	39.35	.53	1.76	23.10
51	18.36	44.78	.41	2.52	19.43
52	18.10	51.72	.35	2.72	20.09
53	20.95	47.62	.44	1.72	28.91
54	17.90	35.10	.51	1.78	20.83
55	17.68	35.36	.50	2.18	17.65
56	17.48	19.00	.92	1.06	18.51
57	19.95	30.70	.65	1.41	23.18
58	17.42	31.10	.56	1.63	19.66
59	16.00	25.40	.63	.94	27.34

HYDRAULIC MEASUREMENTS

FLINT RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
60	15.26	21.80	.70	1.21	18.28
61	17.21	23.90	.72	.93	25.79
62	19.70	19.90	.99	.85	23.58
63	19.98	19.40	1.03	.89	22.32
64	21.44	23.30	.92	1.09	21.89
65	18.35	24.80	.74	1.24	20.11
66	17.05	20.30	.84	.86	23.57
67	20.60	30.30	.68	1.38	23.07
68	22.75	32.50	.70	1.53	22.14
69	22.41	27.00	.83	1.12	24.47
70	19.82	41.30	.48	1.70	24.66
71	24.45	32.60	.75	1.28	25.87
72	25.65	42.75	.60	1.91	23.95
73	26.80	35.26	.76	1.92	19.77
74	24.50	31.01	.79	1.25	25.20
75	24.36	40.60	.60	1.88	24.01
76	25.70	32.12	.80	1.61	20.86
77	25.77	54.83	.47	2.19	26.18
78	25.17	27.66	.91	1.54	18.56
79	22.51	31.70	.71	1.58	20.21

HYDRAULIC MEASUREMENTS

FLINT RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
80	21.53	52.51	.41	1.94	27.63
81	24.89	59.27	.42	2.02	32.13
82	21.06	45.78	.46	1.64	29.51
83	24.00	33.80	.71	1.21	28.68
84	29.19	40.54	.72	1.84	23.05
85	30.44	76.10	.40	1.99	39.46
86	32.99	54.09	.61	1.52	37.31
87	29.54	57.92	.51	2.02	32.41
88	21.21	40.78	.52	1.27	32.49
89	20.82	29.32	.71	1.20	25.67
90	30.97	119.12	.26	1.97	62.85
91	29.67	61.81	.48	1.14	56.36
92	23.59	63.77	.37	2.82	24.69
93	27.54	59.88	.46	1.39	47.18
94	27.40	28.84	.95	1.34	24.20
95	26.11	43.52	.60	.93	47.93
96	26.18	40.28	.65	1.61	26.47
97	32.38	40.47	.80	1.40	31.03
98	29.55	40.48	.73	1.42	29.41
99	23.71	48.38	.49	1.56	32.02

HYDRAULIC MEASUREMENTS

FLINT RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
100	23.16	29.32	.79	1.22	24.88
101	24.55	32.74	.75	1.11	31.09

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
0	10.53	9.40	1.12	.38	42.20
1	34.91	37.54	.93	1.88	20.80
2	46.78	26.58	1.76	1.06	25.47
3	42.19	30.35	1.39	1.17	26.94
4	46.98	31.32	1.50	1.20	26.32
5	43.95	29.90	1.47	.81	37.39
6	50.62	46.44	1.09	1.41	33.89
7	54.95	36.88	1.49	1.08	34.19
8	50.20	33.92	1.48	1.00	34.15
9	53.93	45.70	1.18	.76	60.30
10	59.61	39.22	1.52	.75	52.16
11	47.23	35.25	1.34	.65	54.10
12	50.88	31.80	1.60	.94	34.46
13	41.90	33.52	1.25	1.13	30.18
14	43.14	34.79	1.24	1.16	30.89
15	52.96	34.17	1.55	1.27	27.71
16	59.36	42.40	1.40	1.27	34.08
17	51.97	34.19	1.52	1.05	32.80
18	54.17	32.83	1.65	1.14	28.94
19	53.35	31.20	1.71	1.08	29.64

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
20	56.35	32.20	1.75	.92	35.39
21	55.66	33.33	1.67	1.08	31.30
22	50.89	29.08	1.75	1.12	26.32
23	42.00	32.56	1.29	1.49	22.65
24	39.19	39.59	.99	1.58	25.38
25	39.61	32.47	1.22	.94	34.92
26	77.30	44.17	1.75	1.03	43.28
27	75.52	49.36	1.53	1.02	48.93
28	78.46	51.62	1.52	1.29	40.68
29	94.44	41.24	2.29	1.72	24.58
30	86.39	56.10	1.54	1.87	31.85
31	100.88	60.05	1.68	1.62	37.42
32	86.86	46.46	1.87	1.79	26.66
33	63.16	38.51	1.64	1.51	26.26
34	68.98	48.56	1.42	1.77	28.92
35	83.86	86.45	.97	2.25	40.07
36	83.22	69.35	1.20	1.49	47.65
37	55.97	65.85	.85	1.69	40.03
38	57.73	38.23	1.51	.91	42.31
39	69.13	49.03	1.41	1.14	43.35

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
40	70.35	48.52	1.45	1.20	41.08
41	75.77	79.76	.95	1.99	40.68
42	75.89	63.24	1.20	1.56	42.36
43	79.52	74.32	1.07	1.73	46.07
44	57.63	88.66	.65	2.14	42.29
45	56.00	53.33	1.05	1.29	41.75
46	61.48	46.93	1.31	1.25	38.00
47	84.73	59.25	1.43	1.54	39.45
48	80.93	57.40	1.41	1.71	34.96
49	95.65	71.38	1.34	1.39	51.78
50	87.81	61.84	1.42	1.08	57.12
51	98.12	62.90	1.56	1.03	61.36
52	70.25	56.20	1.25	1.10	51.64
53	71.57	56.80	1.26	1.14	50.31
54	73.91	48.31	1.53	.85	57.22
55	86.36	58.75	1.47	1.20	49.39
56	75.30	54.96	1.37	.98	56.74
57	88.37	69.58	1.27	1.18	59.78
58	98.62	59.41	1.66	1.06	56.33
59	89.43	63.88	1.40	1.10	58.53

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
60	78.21	62.07	1.26	.95	65.54
61	67.45	48.18	1.40	.82	59.34
62	70.00	47.30	1.48	.84	56.27
63	68.75	43.78	1.57	1.04	42.70
64	93.42	54.63	1.71	1.11	49.32
65	98.06	62.86	1.56	1.19	53.15
66	93.46	57.00	1.64	1.39	41.35
67	92.34	61.56	1.50	1.23	50.42
68	64.32	43.17	1.49	1.00	43.59
69	64.60	47.50	1.36	1.22	39.33
70	64.16	45.84	1.40	1.02	45.21
71	71.41	46.37	1.54	1.08	43.21
72	70.90	48.90	1.45	1.16	42.59
73	66.86	43.70	1.53	1.04	42.24
74	65.65	44.95	1.46	1.28	35.83
75	61.74	46.77	1.32	1.09	43.36
76	61.57	41.32	1.49	1.03	40.42
77	65.46	46.10	1.42	1.36	34.17
78	89.90	58.76	1.53	1.28	46.46
79	107.04	68.18	1.57	1.29	53.62

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
80	77.04	52.41	1.47	1.46	37.33
81	89.27	81.90	1.09	1.64	51.05
82	100.55	68.67	1.46	1.68	41.68
83	114.30	77.23	1.48	1.17	66.34
84	107.06	83.04	1.28	1.78	47.69
85	111.39	128.03	.87	2.00	66.25
86	99.71	63.11	1.58	1.66	38.49
87	100.94	107.38	.94	2.15	50.90
88	81.66	71.63	1.14	1.43	50.40
89	88.87	56.97	1.56	1.54	37.91
90	88.41	64.53	1.37	2.08	33.95
91	81.40	61.67	1.32	1.50	41.89
92	80.79	74.12	1.09	1.48	51.37
93	78.16	52.11	1.50	1.58	33.91
94	88.80	59.60	1.49	1.24	48.56
95	90.15	52.41	1.72	1.81	30.23
96	98.51	63.97	1.54	1.12	57.55
97	88.05	59.90	1.47	1.13	53.41
98	85.25	65.56	1.30	2.05	32.41
99	88.31	78.15	1.13	1.50	53.54

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
100	81.31	80.50	1,01	1.87	43.51
101	82.15	61.75	1.33	1.26	49.14
102	88.74	60.78	1.46	1.24	49.05
103	84.75	67.26	1,26	1.53	44.32
104	106.80	70.73	1,51	1.50	48.33
105	100.46	64.40	1,56	1.53	42.33
106	88.60	67.12	1,32	1.68	40.19
107	91.68	77.04	1,19	1.57	49.68
108	102.75	75.00	1,37	1.32	57.49
109	90,99	67.40	1,35	1.68	40.86
110	85.15	96.76	.88	2.02	48.86
111	87,09	95.76	,91	1.50	64.27
112	85.66	100.80	.85	1.83	55.26
113	120.81	145.55	.83	2.35	62.41
114	106.11	129.40	.82	2.35	55.70
115	107.34	178.90	.60	2.80	64.52
116	101.30	72.88	1,39	1.26	58.20
117	102,02	78.48	1,30	1.83	43.15
118	97.85	75.27	1,30	1.51	50.10
119	103.91	91.15	1,14	1.82	50.21

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET,PER. (FT)
120	114.99	81.55	1.41	1.36	60,47
121	128.91	121.61	1.06	2.25	54.86
122	97.36	120.20	.81	2.50	48.23
123	95.90	141.03	.68	2.04	70.17
124	98.10	150.93	.65	2.52	60.67
125	100.80	120.00	.84	2.00	60.86
126	93.98	66.65	1.41	1.39	48,12
127	91.12	78.55	1.16	1.32	59,57
128	87.25	77.90	1.12	1.59	49,41
129	95.36	113.52	.84	2.06	55.58
130	88.52	95.18	.93	1.80	53.28
131	87.69	130.88	.67	2.06	63.82
132	94.65	181.98	.52	2.33	78.60
133	100.72	167.87	.60	2.27	74,28
134	95.24	170.07	.56	2.21	77,34
135	111.27	191.84	.58	2.52	76,49
136	115.69	93.30	1.24	1.37	68,39
137	107.51	182.22	.59	2.85	64,41
138	106.22	96.56	1.10	1.34	72,18
139	100.90	76.44	1.32	.93	82,21

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
140	116.84	80.58	1,45	1.18	68.18
141	111.31	71.35	1,56	1.52	47.24
142	101.96	78.43	1,30	1.49	53.26
143	109.56	89.80	1,22	1.20	75.22
144	109.59	89.10	1,23	1.17	76.49
145	104.73	79.95	1,31	1.16	69.42
146	122.12	104.38	1,17	1.39	75.29
147	124.62	107.43	1,16	1.40	77.90
148	119.54	98.79	1,21	1.30	76.36
149	127.30	116.79	1,09	1.38	85.22
150	183.73	408.30	.45	4.92	85.04
151	126.31	185.75	.68	2.69	69.64
152	136.06	302.35	.45	4.32	71.36
153	131.52	248.15	.53	3.18	79.17
154	116.32	178.95	.65	1.88	95.61
155	123.10	212.25	.58	2.17	98.49
156	121.44	319.58	.38	4.32	77.49
157	134.04	382.98	.35	4.21	92.34
158	149.95	187.44	,80	1.95	97.48
159	124.95	68.28	1,83	1.11	63.51

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
160	114.68	83.10	1.38	1.70	49.79
161	134.09	88.80	1.51	1.31	68.54
162	134.09	91.84	1.46	1.22	76.00
163	122.02	78.22	1.56	1.45	54.12
164	149.85	86.62	1.73	1.92	45.84
165	138.01	91.40	1.51	1.47	62.50
166	134.54	89.10	1.51	1.75	51.95
167	164.40	79.42	2.07	2.41	34.64
168	127.85	95.41	1.34	1.36	70.53
169	122.58	96.52	1.27	1.69	58.13
170	126.00	116.67	1.08	2.01	58.54
171	126.98	104.94	1.21	1.87	56.41
172	129.15	95.67	1.35	1.23	78.29
173	120.11	86.41	1.39	1.15	75.58
174	122.73	100.60	1.22	1.48	68.30
175	120.96	90.27	1.34	1.31	69.86
176	112.01	83.59	1.34	1.33	63.47
1 7	122.43	94.18	1.30	1.74	54.72
178	114.81	83.80	1.37	1.29	65.15
179	121.25	79.25	1.53	1.58	50.91

HYDRAULIC MEASUREMENTS

SOUTH RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
180	.00	.00	.00	.00	5.12
181	110.58	97.00	1.14	1.67	59.01
182	117.63	74.45	1.58	1.26	59.43
183	129.55	107.07	1.21	1.78	61.18
184	105.73	89.60	1.18	1.57	57.56
185	113.78	90.30	1.26	1.29	70.41
186	110.84	95.55	1.16	1.47	66.04
187	126.42	86.59	1.46	1.40	62.71
188	127.45	88.51	1.44	1.05	84.87
189	108.90	89.26	1.22	1.21	74.34
190	122.28	78.89	1.55	1.29	61.13
191	124.26	82.84	1.50	1.34	62.98
192	112.14	88.30	1.27	1.40	63.59
193	140.98	114.62	1.23	1.85	62.82

Reproduced from best available copy.

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
15	1901.90	1330.00	1.43	7.23	187.06
16	1786.51	1063.40	1.68	5.66	190.42
17	1783.98	954.00	1.87	5.30	181.34
18	1780.77	1092.50	1.63	6.43	172.54
19	1781.31	1041.70	1.71	5.69	185.54
20	1669.91	799.00	2.09	4.81	168.09
21	1598.98	757.80	2.11	4.57	167.77
22	1600.20	762.00	2.10	4.76	161.79
23	1599.17	743.80	2.15	4.35	171.98
24	1602.40	965.30	1.66	5.45	178.55
25	1528.80	1092.00	1.40	5.75	192.29
26	1528.81	899.30	1.70	5.29	175.01
27	1531.86	855.80	1.79	4.58	189.52
28	1528.18	701.00	2.18	3.89	181.31
29	1532.49	726.30	2.11	4.54	161.79
30	882.65	695.00	1.27	4.34	162.37
31	910.03	674.10	1.35	4.29	158.30
32	908.28	783.00	1.16	4.89	161.44
33	914.20	653.00	1.40	3.63	181.12
34	913.50	609.00	1.50	3.95	155.35
35	941.70	645.00	1.46	4.03	161.05

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
36	960.81	807.40	1.19	5.49	149.37
37	961.20	534.00	1.80	3.81	141.47
38	962.92	724.00	1.33	4.26	172.17
39	956.82	777.90	1.23	4.99	157.77
40	981.25	785.00	1.25	4.36	181.81
41	986.49	809.00	1.22	4.54	180.85
42	992.16	689.00	1.44	4.05	171.55
43	991.29	573.00	1.73	3.82	150.99
44	986.85	765.00	1.29	4.78	161.47
45	1002.73	539.10	1.86	3.43	158.35
46	877.82	636.10	1.38	3.90	164.50
47	881.60	431.90	2.04	2.73	159.14
48	881.79	531.20	1.66	3.14	169.96
49	1052.53	608.40	1.73	3.44	178.77
50	881.79	663.00	1.33	4.28	156.72
51	861.96	422.50	2.04	2.40	177.00
52	859.70	760.80	1.13	4.85	158.93
53	863.25	777.70	1.11	4.39	178.94
54	862.99	725.20	1.19	4.34	168.67
55	844.76	431.00	1.96	2.17	199.60

Reproduced from best available copy.

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
56	858.30	514.00	1.67	3.06	169.01
57	858.90	734.10	1.17	4.43	165.60
58	855.65	383.70	2.23	2.35	163.93
59	857.04	495.40	1.73	3.20	156.04
60	866.20	710.00	1.22	4.67	153.61
61	867.77	657.40	1.32	4.47	148.72
62	871.00	435.50	2.00	2.59	168.93
63	869.65	496.00	1.75	3.10	160.70
64	870.87	565.50	1.54	3.43	166.17
65	869.44	608.00	1.43	3.33	181.64
66	1163.25	930.00	1.25	5.57	169.30
67	1163.12	868.00	1.34	5.17	171.70
68	1162.39	621.60	1.87	3.84	163.04
69	1161.32	784.00	1.48	5.23	151.85
70	1155.90	684.00	1.69	4.38	157.37
71	1160.00	763.20	1.52	4.41	175.07
72	1162.30	590.00	1.97	3.69	161.43
73	1150.80	411.00	2.80	2.74	150.90
74	1152.21	579.00	1.99	3.62	161.20
75	1146.99	754.60	1.52	5.13	149.33

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
76	1095.16	720.50	1.52	4.26	170.77
77	1095.46	601.90	1.82	3.52	172.86
78	1100.26	636.00	1.73	3.83	168.70
79	1099.16	506.50	2.17	3.47	147.28
80	1048.92	659.70	1.59	4.12	161.95
81	1051.34	735.20	1.43	4.90	152.36
82	1051.54	649.10	1.62	3.84	172.40
83	1049.79	558.40	1.88	3.10	181.24
84	1051.35	653.00	1.61	4.08	162.31
85	944.67	651.50	1.45	4.34	152.29
86	947.83	649.20	1.46	4.49	147.35
87	946.99	653.10	1.45	4.50	147.27
88	1059.22	657.90	1.61	3.94	168.53
89	1058.79	710.60	1.49	4.33	166.32
90	1058.93	678.80	1.56	4.65	148.22
91	1077.25	695.00	1.55	4.06	172.67
92	1098.24	747.10	1.47	4.39	171.62
93	1121.93	587.40	1.91	4.45	134.09
94	1133.62	542.40	2.09	3.31	165.52
95	1005.65	581.30	1.73	3.68	162.46

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
96	1007.51	451.60	2.23	3.09	148.94
97	1008.40	491.90	2.05	3.22	156.09
98	1006.43	529.70	1.90	3.56	152.74
99	842.34	478.60	1.76	3.23	148.93
100	841.13	485.20	1.73	3.29	149.33
101	840.67	509.50	1.65	3.29	156.69
102	841.53	568.60	1.48	3.95	145.51
103	.00	.00	.00	.00	.00
104	1900.31	819.10	2.32	4.93	168.00
105	1902.81	861.00	2.21	5.09	172.15
106	1884.67	981.60	1.92	5.58	178.54
107	1785.93	915.40	1.95	5.06	184.01
108	1683.14	940.30	1.79	5.40	176.24
109	1570.60	872.60	1.80	5.70	155.67
110	1471.60	672.00	2.19	5.33	128.03
111	1367.57	949.70	1.44	5.55	174.87
112	1296.00	810.00	1.60	4.63	177.19
113	1613.60	996.10	1.62	5.89	172.26
114	1553.20	958.80	1.62	5.07	192.26
115	1492.40	910.00	1.64	4.84	192.02

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
116	1426.11	932.10	1.53	5.75	164.31
117	1370.45	736.80	1.86	4.09	182.10
118	1313.60	746.40	1.76	4.22	179.86
119	1247.32	670.60	1.86	4.66	146.90
120	1183.21	717.10	1.65	4.54	160.59
121	1121.37	752.60	1.49	4.62	165.32
122	1061.60	717.30	1.48	4.49	162.27
123	1000.24	813.20	1.23	4.78	172.43
124	1101.13	754.20	1.46	4.01	190.16
125	1533.01	923.50	1.66	4.55	204.36
126	919.36	557.20	1.65	2.81	199.29
127	919.10	505.00	1.82	2.30	221.44
128	921.12	606.00	1.52	3.52	173.76
129	921.56	579.60	1.59	2.97	196.49
130	916.35	615.00	1.49	3.27	189.80
131	912.60	574.00	1.59	2.76	209.89
132	913.50	550.30	1.66	2.79	198.73
133	913.25	543.60	1.68	2.63	208.50
134	913.42	543.70	1.68	2.44	224.94
135	1124.37	576.60	1.95	2.93	198.16

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
136	1097.82	609.90	1.80	3.08	200.70
137	1099.45	591.10	1.86	3.46	173.00
138	1098.37	603.50	1.82	3.66	167.22
139	1070.35	733.10	1.46	4.31	172.01
140	1057.95	705.30	1.50	4.30	167.64
141	1048.24	635.30	1.65	3.33	191.80
142	1047.46	609.00	1.72	3.01	203.30
143	1050.70	644.60	1.63	3.60	180.75
144	1047.39	560.10	1.87	2.81	199.97
145	1051.65	653.20	1.61	3.61	183.68
146	1048.95	499.50	2.10	3.03	166.26
147	1117.10	594.20	1.88	3.30	182.50
148	.00	.00	.00	.00	.00
149	1120.87	647.90	1.73	3.29	198.39
150	.00	.00	.00	.00	.00
151	1119.90	670.60	1.67	3.39	199.12
152	.00	.00	.00	.00	.00
153	1125.02	650.30	1.73	3.83	170.91
154	.00	.00	.00	.00	.00
155	1103.13	648.90	1.70	3.55	184.26

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
156	.00	.00	.00	.00	.00
157	1077.15	656.80	1.64	3.49	189.82
158	.00	.00	.00	.00	.00
159	1058.99	720.40	1.47	5.42	135.69
160	.00	.00	.00	.00	.00
161	1042.84	739.60	1.41	4.57	164.25
162	.00	.00	.00	.00	.00
163	1030.80	687.20	1.50	3.54	194.98
164	.00	.00	.00	.00	.00
165	1058.05	594.40	1.78	2.99	200.19
166	.00	.00	.00	.00	.00
167	1092.01	535.30	2.04	3.48	154.94
168	.00	.00	.00	.00	.00
169	1130.62	642.40	1.76	3.61	363.80
170	.00	.00	.00	.00	.00
171	1169.32	754.40	1.55	4.31	177.58
172	.00	.00	.00	.00	.00
173	1214.21	793.60	1.53	4.22	189.81
174	.00	.00	.00	.00	.00
175	1210.47	771.00	1.57	4.28	182.32

HYDRAULIC MEASUREMENTS

CHATTAHOOCHEE RIVER

STA.	FLOW (CFS)	AREA (SQ FT)	VEL. (FPS)	DEPTH (FT)	WET.PER. (FT)
176	.00	.00	.00	.00	.00
177	1209.46	817.20	1.48	4.62	179.52
178	.00	.00	.00	.00	.00
179	1303.01	886.40	1.47	4.74	190.46
180	.00	.00	.00	.00	.00
181	1302.85	819.40	1.59	4.34	191.42
182	.00	.00	.00	.00	.00
183	1303.54	835.60	1.56	4.52	188.17
184	.00	.00	.00	.00	.00
185	1296.17	815.20	1.59	4.12	199.96
186	.00	.00	.00	.00	.00
187	1301.30	770.00	1.69	4.53	172.33
188	.00	.00	.00	.00	.00
189	.00	.00	.00	.00	.00
190	1303.60	874.90	1.49	4.46	197.90
191	.00	.00	.00	.00	.00
192	.00	.00	.00	.00	.00
193	1260.54	829.30	1.52	3.84	217.70
194	.00	.00	.00	.00	.00
195	1227.85	870.80	1.41	3.61	242.37

APPENDIX AIV

DETAILED TRACER STUDY RESULTS AND REAERATION COEFFICIENTS

FIELD TRACER DATA

FLINT RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
I	0-1	.2399	.1199	3.030	19.0	.2287	.3140	.5460	.4539	23.83	7.86
	0-2	.2399	.0290	6.960	16.7	.3031	.4375	.9201	.0798	51.65	7.42
	1-2	.1199	.0290	3.930	15.0	.3605	.5399	.8281	.1718	27.82	7.07
II	1-2P	.2223	.1124	3.120	21.5	.2183	.2839	.5206	.4793	15.80	5.06
	1-2	.2223	.0558	3.470	21.3	.3983	.5201	.7764	.2235	27.83	8.02
	1-3	.2223	.0406	5.040	20.4	.3371	.4489	.8470	.1529	37.25	7.39
	1-4	.2223	.0153	10.240	18.7	.2609	.3606	.9533	.0466	57.76	5.64
	2P-2	.1124	.0558	.350	19.5	2.0026	2.7195	.5461	.4538	12.03	34.37
	2P-3	.1124	.0406	1.920	18.7	.5300	.7324	.6887	.3112	21.45	11.17
	2P-4	.1124	.0153	7.120	17.5	.2796	.3966	.9040	.0959	41.96	5.89
	2-3	.0558	.0406	1.570	18.5	.2017	.2800	.3057	.6942	9.42	6.00
	2-4	.0558	.0153	6.770	17.3	.1905	.2714	.7824	.2175	29.93	4.42
	3-4	.0406	.0153	5.200	17.0	.1871	.2683	.6859	.3140	20.51	3.94
III	0-1P	.1955	.1328	2.720	26.5	.1421	.1658	.3122	.6877	9.88	3.63
	0-1	.1955	.0664	2.798	26.5	.3855	.4496	.6480	.3519	23.83	8.51
	0-2P	.1955	.0331	6.050	26.4	.2935	.3430	.8213	.1786	39.58	6.54
	0-2	.1955	.0152	6.470	26.4	.3946	.4612	.9159	.0840	51.65	7.98
	0-3	.1955	.0112	7.998	26.1	.3568	.4197	.9383	.0616	61.07	7.63
	1P-1	.1328	.0664	.078	27.0	8.8729	10.2350	.4844	.5155	13.95	178.84
	1P-2P	.1328	.0331	3.328	26.4	.4173	.4877	.7400	.2599	29.70	8.92
	1P-2	.1328	.0152	3.745	26.3	.5785	.6775	.8782	.1217	41.77	11.15
	1P-3	.1328	.0112	5.278	25.9	.4674	.5513	.9106	.0893	51.19	9.69
	1-2P	.0664	.0331	3.250	26.4	.2144	.2506	.4913	.5086	15.75	4.84
	1-2	.0664	.0152	3.667	26.3	.4020	.4709	.7614	.2385	27.82	7.58
	1-3	.0664	.0112	5.200	25.9	.3413	.4028	.8242	.1757	37.24	7.16

FIELD TRACER DATA

FLINT RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
III	2P-2	.0331	.0152	.417	25.6	1.8645	2.2173	.5358	.4641	12.07	28.94
	2P-3	.0331	.0112	1.950	25.2	.5528	.6631	.6581	.3418	21.49	11.02
	2-3	.0152	.0112	1.533	25.1	.1959	.2356	.2590	.7409	9.42	6.14
IV	3*-BS	.1598	.1173	1.430	21.4	.2160	.2815	.2840	.7159	5.30	3.70
	3*-AS	.1598	.0936	2.900	21.4	.1843	.2401	.4390	.5609	9.08	3.13
	3*-F	.1598	.0755	3.420	21.5	.2192	.2850	.5547	.4452	15.64	4.57
	3*-4	.1598	.0643	4.950	21.9	.1837	.2364	.6214	.3785	19.31	3.90
	3*-5	.1598	.0398	9.450	22.8	.1468	.1852	.7662	.2337	27.39	2.89
	3*-6	.1598	.0339	14.770	23.3	.1048	.1310	.7994	.2005	36.11	2.44
	BS-AS	.1173	.0936	1.470	21.4	.1534	.1999	.2164	.7835	3.78	2.57
	BS-F	.1173	.0755	1.990	21.6	.2215	.2873	.3778	.6221	10.34	5.19
	BS-4	.1173	.0643	3.520	22.2	.1705	.2184	.4717	.5282	14.01	3.98
	BS-5	.1173	.0398	8.020	23.2	.1345	.1686	.6744	.3255	22.09	2.75
	BS-6	.1173	.0339	13.340	23.5	.0928	.1156	.7220	.2779	30.81	2.30
	AS-F	.0936	.0755	.520	22.0	.4139	.5323	.2052	.7947	6.56	12.61
	AS-4	.0936	.0643	2.050	22.8	.1828	.2310	.3251	.6748	10.23	4.99
	AS-5	.0936	.0398	6.550	23.5	.1303	.1622	.5860	.4139	18.31	2.79
	AS-6	.0936	.0339	11.370	23.7	.0854	.1058	.6475	.3524	27.03	2.27
	F-4	.0755	.0643	1.533	23.0	.1040	.1309	.1535	.8464	3.67	2.39
	F-5	.0755	.0398	6.030	23.7	.1058	.1312	.4814	.5185	11.75	1.94
	F-6	.0755	.0339	11.350	23.8	.0703	.0870	.5593	.4406	20.47	1.80
	4-5	.0643	.0398	4.500	23.9	.1064	.1313	.3876	.6123	8.08	1.79
	4-6	.0643	.0339	9.820	23.9	.0650	.0802	.4802	.5197	16.80	1.71
	5-6	.0398	.0339	5.320	23.9	.0300	.0371	.1512	.8487	8.72	1.63

FIELD TRACER DATA

FLINT RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
V	4-5	.5729	.3728	4.550	24.0	.0944	.1162	.3553	.6446	7.83	1.72
	4-6	.5729	.2419	9.900	24.1	.0870	.1069	.5848	.4151	16.71	1.68
	4-7	.5729	.1134	17.730	24.2	.0913	.1119	.8075	.1924		
	5-6	.3728	.2419	5.350	24.2	.0808	.0990	.3559	.6440	8.88	1.65
	5-7	.3728	.1134	13.180	24.3	.0902	.1104	.7011	.2988		
	6-7	.2419	.1134	7.830	24.3	.0967	.1183	.5364	.4635		
XII	4-5	.2952	.2075	4.670	22.0	.0754	.0970	.3134	.6865	7.92	1.69
	4-6	.2952	.1329	10.240	22.3	.0779	.0995	.5710	.4289	16.00	1.56
	4-7	.2952	.0594	18.320	22.6	.0875	.1110	.8153	.1846		
	5-6	.2075	.1329	5.570	22.5	.0800	.1018	.3754	.6245	8.08	1.45
	5-7	.2075	.0594	13.650	22.8	.0916	.1158	.7307	.2692		
	6-7	.1329	.0594	8.080	23.0	.0996	.1253	.5686	.4313		
XIV	0-R1	.5392	.4044	1.750	24.0	.1642	.2023	.2546	.7453	3.49	1.99
	0-R2	.5392	.3654	1.800	24.0	.2160	.2660	.3279	.6720	5.56	3.08
	0-R3	.5392	.3222	1.870	24.0	.2752	.3389	.4091	.5908	7.93	4.24
	0-1P	.5392	.3092	4.740	24.3	.1172	.1434	.4312	.5687	10.04	2.11
	0-1	.5392	.1224	4.810	24.3	.3081	.3769	.7780	.2219	23.86	4.96
	0-2P	.5392	.0503	8.880	24.1	.2670	.3281	.9109	.0890	39.89	4.49
	0-2	.5392	.0172	9.340	24.1	.3688	.4531	.9701	.0298	51.74	5.53
	R1-R2	.4044	.3654	.050	24.0	2.0283	2.4975	.0984	.9015	2.07	41.40
	R1-R3	.4044	.3222	.117	24.0	1.9425	2.3918	.2072	.7927	4.44	37.94
	R1-1P	.4044	.3092	2.990	24.5	.0897	.1093	.2375	.7624	6.55	2.19
	R1-1	.4044	.1224	3.060	24.5	.3904	.4755	.7011	.2988	20.37	6.65
	R1-2P	.4044	.0503	7.130	24.1	.2922	.3591	.8805	.1194	36.40	5.10
	R1-2	.4044	.0172	7.590	24.1	.4159	.5110	.9600	.0399	48.25	6.35

FIELD TRACER DATA

FLINT RIVER

Dump No.	Reach	Observed Kr:H Ratio Upstr	Observed Kr:H Ratio Dnstr	Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C lost	% Tracer Gas 25°C rem	WS Elev Chnge ft	WS Elev Chnge ft/hr
XIV	R2-R3	.3654	.3222	.067	24.0	1.8784	2.3129	.1206	.8793	2.37	35.37
	R2-1P	.3654	.3092	2.940	24.5	.0567	.0691	.1552	.8447	4.48	1.52
	R2-1	.3654	.1224	3.010	24.5	.3632	.4424	.6689	.3310	18.30	6.07
	R2-2P	.3654	.0503	7.080	24.1	.2800	.3440	.8675	.1324	34.33	4.84
	R2-2	.3654	.0172	7.540	24.1	.4052	.4979	.9556	.0443	46.18	6.12
	R3-1P	.3222	.3092	2.870	24.5	.0143	.0174	.0406	.9593	2.11	.73
	R3-1	.3222	.1224	2.950	24.5	.3279	.3994	.6239	.3760	15.93	5.40
	R3-2P	.3222	.0503	7.020	24.1	.2644	.3249	.8494	.1505	31.96	4.55
	R3-2	.3222	.0172	7.470	24.1	.3922	.4818	.9496	.0503	43.81	5.86
	1P-1	.3092	.1224	.075	24.3	12.3532	15.1119	.6096	.3903	13.82	184.26
	1P-2P	.3092	.0503	4.150	23.8	.4375	.5410	.8449	.1550	29.85	7.19
	1P-2	.3092	.0172	4.600	23.8	.6279	.7766	.9484	.0515	41.70	9.06
	1-2P	.1224	.0503	4.070	23.8	.2184	.2701	.5985	.4014	16.03	3.93
	1-2	.1224	.0172	4.530	23.8	.4331	.5357	.8665	.1334	27.88	6.15
	2P-2	.0503	.0172	.458	24.0	2.3430	2.8850	.6660	.3339	11.85	25.87

FIELD TRACER DATA

SOUTH RIVER

Dump No.	Reach	Observed Kr:H Ratio Upstr	Dnstr	Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C lost	rem	WS Elev Chnge ft	ft/hr
VI	A-B	.5359	.3345	2.480	22.1	.1900	.2438	.3946	.6053	12.07	4.86
	A-D	.5359	.2280	3.850	22.1	.2219	.2847	.5974	.4025	24.00	6.23
	A-E	.5359	.1532	6.280	22.7	.1993	.2524	.7318	.2681	36.47	5.80
	A-F	.5359	.1164	7.980	23.2	.1913	.2397	.7955	.2044	44.81	5.61
	B-D	.3345	.2280	1.370	22.2	.2796	.3580	.3344	.6655	11.93	8.70
	B-E	.3345	.1532	3.800	23.0	.2053	.2584	.5574	.4425	24.40	6.42
	B-F	.3345	.1164	5.500	23.7	.1918	.2378	.6623	.3376	32.74	5.95
	D-E	.2280	.1532	2.430	23.5	.1635	.2035	.3367	.6632	12.47	5.13
	D-F	.2280	.1164	4.130	24.2	.1627	.1995	.4954	.5045	20.81	5.03
	E-F	.1532	.1164	1.700	25.3	.1616	.1935	.2389	.7610	8.34	4.90
VII	G-H	.5014	.3641	.433	23.5	.7391	.9200	.2815	.7184	7.67	17.71
	G-J	.5014	.1922	3.550	23.5	.2700	.3361	.6285	.3714	21.88	6.16
	G-K	.5014	.1941	6.820	23.6	.1391	.1728	.6240	.3759	24.03	3.52
	G-L	.5014	.1018	7.000	23.6	.2277	.2829	.8067	.1932	36.15	5.16
	H-J	.3641	.1922	3.120	23.5	.2046	.2547	.4830	.5169	14.21	4.55
	H-K	.3641	.1941	6.380	23.6	.0985	.1224	.4771	.5228	16.36	2.56
	H-L	.3641	.1018	6.570	23.6	.1939	.2409	.7312	.2687	28.48	4.33
	J-K	.1922	.1941	3.270	23.7	-.0029	-.0036	-.0098	1.0098	2.15	.65
	J-L	.1922	.1018	3.450	23.7	.1843	.2284	.4801	.5198	14.27	4.13
	K-L	.1941	.1018	.184	24.1	3.5082	4.3104	.4822	.5177	12.12	65.86
VIII	J-K	.5341	.4104	2.720	23.9	.0968	.1194	.2364	.7635	2.14	.78
	J-L	.5341	.2998	3.000	23.9	.1923	.2374	.4463	.5536	14.31	4.77
	J-M	.5341	.2709	4.850	24.3	.1399	.1712	.4980	.5019	19.02	3.92
	J-N	.5341	.2108	7.300	24.7	.1273	.1543	.6075	.3924	28.02	3.84
	K-L	.4104	.2998	.283	23.9	1.1088	1.3668	.2746	.7253	12.17	43.00

FIELD TRACER DATA

SOUTH RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
VIII	K-M	.4104	.2709	2.130	24.7	.1950	.2365	.3417	.6582	16.88	7.92
	K-N	.4104	.2108	4.580	25.1	.1454	.1748	.4854	.5145	25.88	5.65
	L-M	.2998	.2709	1.850	24.8	.0549	.0664	.0970	.9029	4.71	2.54
	L-N	.2998	.2108	4.300	25.2	.0818	.0982	.2957	.7042	13.71	3.19
	M-N	.2709	.2108	2.450	25.5	.1022	.1218	.2195	.7804	9.00	3.67
IX	E-F	.4484	.3484	1.780	23.0	.1416	.1782	.2315	.7684	8.56	4.80
	E-G	.4484	.2037	6.530	23.7	.1207	.1496	.5557	.4442	24.15	3.69
	E-H	.4484	.1587	7.170	23.7	.1447	.1794	.6562	.3437	31.29	4.36
	E-J	.4484	.0767	10.600	23.9	.1664	.2054	.8359	.1640	45.49	4.29
	E-K	.4484	.0543	13.820	24.0	.1526	.1879	.8842	.1157	47.74	3.45
	F-G	.3484	.2037	4.750	23.9	.1129	.1393	.4227	.5772	15.59	3.28
	F-H	.3484	.1587	5.380	23.9	.1461	.1800	.5524	.4475	22.73	4.22
	F-J	.3484	.0767	8.820	24.0	.1715	.2111	.7869	.2130	36.93	4.18
	F-K	.3484	.0543	12.030	24.2	.1544	.1893	.8489	.1510	39.18	3.25
	G-H	.2037	.1587	.633	24.3	.3941	.4822	.2238	.7761	7.14	11.27
	G-J	.2037	.0767	4.070	24.2	.2398	.2940	.6296	.3703	21.34	5.24
	G-K	.2037	.0543	7.280	24.4	.1814	.2215	.7377	.2622	23.59	3.24
	H-J	.1587	.0767	3.430	24.2	.2118	.2597	.5226	.4773	14.20	4.13
	H-K	.1587	.0543	6.650	24.3	.1611	.1971	.6631	.3368	16.45	2.47
	J-K	.0767	.0543	3.220	24.5	.1071	.1305	.2944	.7055	2.25	.69
X	A-B	.4997	.3561	2.420	26.2	.1399	.1642	.2810	.7189	11.93	4.92
	A-D	.4997	.2582	3.720	26.3	.1775	.2079	.4737	.5262	23.63	6.35
	A-E	.4997	.1899	6.130	26.9	.1578	.1824	.6047	.3952	35.53	5.79
	A-F	.4997	.1425	7.830	27.3	.1601	.1835	.6966	.3033	44.68	5.70
	B-D	.3561	.2582	1.300	26.4	.2474	.2891	.2680	.7319	11.70	9.00
	B-E	.3561	.1899	3.720	27.2	.1689	.1940	.4507	.5492	23.60	6.34

FIELD TRACER DATA

SOUTH RIVER

Dump No.	Reach	Observed Kr:H Ratio Upstr	Observed Kr:H Ratio Dnstr	Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{cx} 25°C	% Tracer Gas 25°C lost	% Tracer Gas 25°C rem	WS Elev Chnge ft	WS Elev Chnge ft/hr
X	B-F	.3561	.1425	5.410	27.8	.1692	.1918	.5774	.4225	32.75	6.05
	D-E	.2582	.1899	2.420	27.7	.1268	.1441	.2513	.7486	11.90	4.91
	D-F	.2582	.1425	4.110	28.2	.1444	.1623	.4253	.5746	21.05	5.12
	E-F	.1899	.1425	1.690	28.9	.1697	.1878	.2316	.7683	9.15	5.41
XI	F-G	.4591	.2969	4.630	25.9	.0941	.1112	.3477	.6522	15.67	3.38
	F-H	.4591	.2181	5.250	25.9	.1417	.1675	.5180	.4819	23.16	4.41
	F-J	.4591	.0964	8.680	26.0	.1797	.2118	.7827	.2172	37.35	4.30
	F-K	.4591	.0721	12.250	26.4	.1510	.1765	.8338	.1661	39.58	3.23
	G-H	.2969	.2181	.617	25.8	.5000	.5921	.2615	.7384	7.49	12.13
	G-J	.2969	.0964	4.050	26.2	.2775	.3258	.6655	.3344	21.68	5.35
	G-K	.2969	.0721	7.620	26.7	.1856	.2155	.7442	.2557	23.91	3.13
	H-J	.2181	.0964	3.430	26.3	.2378	.2785	.5474	.4525	14.19	4.13
	H-K	.2181	.0721	7.000	26.8	.1580	.1830	.6548	.3451	16.42	2.34
	J-K	.0964	.0721	3.570	27.2	.0813	.0934	.2419	.7580	2.23	.62
XIII	J-K	1.3811	1.2755	3.500	23.5	.0227	.0282	.0788	.9211	2.17	.62
	J-L	1.3811	.7188	3.720	23.5	.1755	.2185	.4907	.5092	14.17	3.80
	J-M	1.3811	.6027	5.950	23.9	.1393	.1719	.5722	.4277	19.26	3.23
	J-N	1.3811	.3958	8.870	24.1	.1408	.1731	.7204	.2795	28.26	3.19
	K-L	1.2755	.7188	.217	24.0	2.6431	3.2545	.4435	.5564	12.00	55.29
	K-M	1.2755	.6027	2.450	24.4	.3059	.3734	.5320	.4679	17.09	6.97
	K-N	1.2755	.3958	5.370	24.5	.2179	.2654	.6936	.3063	26.09	4.86
	L-M	.7188	.6027	2.230	24.5	.0789	.0961	.1630	.8369	5.09	2.28
	L-N	.7188	.3958	5.150	24.5	.1158	.1411	.4529	.5470	14.09	2.74
	M-N	.6027	.3958	2.920	24.5	.1440	.1754	.3463	.6536	9.00	3.08

FIELD TRACER DATA

SOUTH RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
XV	G*-T2	.5097	.4242	.203	17.5	.9037	1.2819	.1942	.8057	4.86	23.94
	G*-H	.5097	.4298	.462	17.1	.3690	.5280	.1832	.8167	5.75	12.45
	G*-J	.5097	.2367	3.670	17.5	.2089	.2964	.5946	.4053	20.02	5.46
	G*-S	.5097	.2368	4.470	17.8	.1714	.2416	.5919	.4080	21.31	4.77
	G*-K	.5097	.1981	7.270	18.6	.1299	.1799	.6623	.3376	22.20	3.05
	G*-L	.5097	.1233	7.480	18.6	.1897	.2627	.8043	.1956	34.27	4.58
	T2-H	.4242	.4298	.259	16.8	-.0500	-.0721	-.0156	1.0156	.89	3.43
	T2-J	.4242	.2367	3.460	17.6	.1686	.2386	.4961	.5038	15.16	4.38
	T2-S	.4242	.2368	4.260	17.9	.1368	.1924	.4935	.5064	16.45	3.86
	T2-K	.4242	.1981	7.060	18.6	.1078	.1493	.5831	.4168	17.34	2.45
	T2-L	.4242	.1233	7.280	18.7	.1697	.2345	.7576	.2423	29.41	4.03
	H-J	.4298	.2367	3.210	17.6	.1858	.2629	.5037	.4962	14.27	4.44
	H-S	.4298	.2368	4.010	17.9	.1485	.2089	.5011	.4988	15.56	3.88
	H-K	.4298	.1981	6.810	18.7	.1136	.1571	.5885	.4114	16.45	2.41
	H-L	.4298	.1233	7.020	18.7	.1778	.2458	.7612	.2387	28.52	4.06
	J-S	.2367	.2368	.800	19.0	-.0007	-.0010	-.0006	1.0006	1.29	1.61
	J-K	.2367	.1981	3.600	19.6	.0493	.0669	.1811	.8188	2.18	.60
	J-L	.2367	.1233	3.820	19.6	.1707	.2313	.5198	.4801	14.25	3.73
	S-K	.2368	.1981	2.800	19.8	.0636	.0859	.1810	.8189	.89	.31
	S-L	.2368	.1233	3.020	19.8	.2161	.2916	.5186	.4813	12.96	4.29
	K-L	.1981	.1233	.217	20.3	2.1868	2.9185	.4088	.5911	12.07	55.62

FIELD TRACER DATA

PATUXENT RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
A	4-5	.7960	.3850	6.700	21.6	.1084	.1406	.5425	.4574	14.70	2.19
	4-6	.7960	.1990	13.920	21.8	.0995	.1286	.7737	.2262	23.20	1.66
	4-7	.7960	.1040	17.520	21.7	.1161	.1503	.8877	.1122	29.60	1.68
	5-6	.3850	.1990	7.220	22.0	.0914	.1175	.5056	.4943	8.50	1.17
	5-7	.3850	.1040	10.820	21.8	.1209	.1562	.7542	.2457	14.90	1.37
	6-7	.1990	.1040	3.600	21.5	.1802	.2343	.5035	.4964	6.40	1.77
B	1-2	.8700	.5390	3.850	22.2	.1243	.1592	.3988	.6011	7.00	1.81
	1-3	.8700	.3650	9.080	22.4	.0956	.1219	.6011	.3988	11.80	1.29
	1-4	.8700	.2110	14.750	22.5	.0960	.1221	.7759	.2240	21.90	1.48
	2-3	.5390	.3650	5.230	22.5	.0745	.0948	.3374	.6625	4.80	.91
	2-4	.5390	.2110	10.900	22.6	.0860	.1092	.6277	.3722	14.90	1.36
	3-4	.3650	.2110	5.670	22.6	.0966	.1226	.4386	.5613	10.10	1.78
C	4-5	.8240	.4350	5.280	20.8	.1209	.1597	.5033	.4966	14.70	2.78
	4-6	.8240	.2720	11.260	21.3	.0984	.1285	.6991	.3008	23.20	2.06
	4-7	.8240	.1550	14.490	21.3	.1153	.1505	.8364	.1635	29.60	2.04
	5-6	.4350	.2720	5.980	21.8	.0785	.1014	.3955	.6044	8.50	1.42
	5-7	.4350	.1550	9.210	21.7	.1120	.1450	.6700	.3299	14.90	1.61
	6-7	.2720	.1550	3.230	21.4	.1741	.2268	.4556	.5443	6.40	1.98
D	1-2	.7430	.5230	2.750	21.3	.1276	.1667	.3165	.6834	7.00	2.54
	1-3	.7430	.3350	7.270	20.8	.1095	.1446	.5822	.4177	11.80	1.62
	1-4	.7430	.1970	11.940	20.2	.1111	.1487	.7709	.2290	21.90	1.83
	2-3	.5230	.3350	4.520	20.5	.0985	.1309	.3881	.6118	4.80	1.06
	2-4	.5230	.1970	9.190	19.9	.1062	.1430	.6641	.3358	14.90	1.62
	3-4	.3350	.1970	4.670	19.3	.1136	.1550	.4517	.5482	10.10	2.16

FIELD TRACER DATA

PATUXENT RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
E	4-5	.6370	.3100	7.620	17.3	.0945	.1346	.5732	.4267	14.70	1.92
	4-6	.6370	.1920	15.770	17.4	.0760	.1081	.7570	.2429	23.20	1.47
	4-7	.6370	.1320	19.730	17.2	.0797	.1138	.8451	.1548	29.60	1.50
	5-6	.3100	.1920	8.150	17.4	.0587	.0835	.4317	.5682	8.50	1.04
	5-7	.3100	.1320	12.110	17.2	.0705	.1006	.6364	.3635	14.90	1.23
	6-7	.1920	.1320	3.960	16.8	.0946	.1362	.3610	.6389	6.40	1.61

FIELD TRACER DATA

JACKSON RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
10	0-1	.3220	.2510	1.650	35.0	.1509	.1463	.1815	.8184	8.20	4.96
	0-2	.3220	.1600	5.970	32.8	.1171	.1191	.4457	.5542	17.50	2.93
	0-3	.3220	.0760	12.670	31.3	.1139	.1197	.7160	.2839	32.00	2.52
	0-4	.3220	.0558	17.090	31.0	.1025	.1084	.7852	.2147	39.40	2.30
	1-2	.2510	.1600	4.320	32.0	.1042	.1078	.3206	.6793	9.30	2.15
	1-3	.2510	.0760	11.020	30.8	.1084	.1151	.6511	.3488	23.80	2.15
	1-4	.2510	.0558	15.440	30.6	.0973	.1038	.7358	.2641	31.20	2.02
	2-3	.1600	.0760	6.700	30.0	.1111	.1200	.4871	.5128	14.50	2.16
	2-4	.1600	.0558	11.120	30.0	.0947	.1023	.6112	.3887	21.90	1.96
	3-4	.0760	.0558	4.420	30.0	.0699	.0755	.2420	.7579	7.40	1.67
11	0-1	1.6780	1.3000	1.850	35.0	.1379	.1337	.1856	.8143	8.20	4.43
	0-2	1.6780	.6840	6.580	32.8	.1363	.1386	.5310	.4689	17.50	2.65
	0-3	1.6780	.4000	12.780	31.5	.1121	.1173	.7119	.2880	32.00	2.50
	0-4	1.6780	.3040	17.380	31.1	.0982	.1037	.7759	.2240	39.40	2.26
	1-2	1.3000	.6840	4.730	32.0	.1357	.1404	.4238	.5761	9.30	1.96
	1-3	1.3000	.4000	10.930	30.9	.1078	.1142	.6453	.3546	23.80	2.17
	1-4	1.3000	.3040	15.530	30.6	.0935	.0997	.7237	.2762	31.20	2.00
	2-3	.6840	.4000	6.200	30.0	.0865	.0935	.3819	.6180	14.50	2.33
	2-4	.6840	.3040	10.800	30.0	.0750	.0811	.5168	.4831	21.90	2.02
	3-4	.4000	.3040	4.600	30.0	.0596	.0644	.2181	.7818	7.40	1.60

FIELD TRACER DATA

JACKSON RIVER

Dump No.	Reach	Observed Kr:H Ratio Upstr	Observed Kr:H Ratio Dnstr	Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C lost	% Tracer Gas 25°C rem	WS Elev Chnge ft	WS Elev Chnge ft/hr
12	4-5	1.6680	1.1230	2.920	28.0	.1354	.1529	.3096	.6903	8.80	3.01
	4-6	1.6680	.7720	7.370	28.6	.1045	.1164	.5095	.4904	16.80	2.27
	4-7	1.6680	.5120	10.750	28.7	.1098	.1221	.6636	.3363	23.00	2.13
	4-8	1.6680	.2960	15.330	28.8	.1127	.1251	.7964	.2035	38.50	2.51
	5-6	1.1230	.7720	4.450	29.0	.0842	.0930	.2907	.7092	8.00	1.79
	5-7	1.1230	.5120	7.830	29.0	.1003	.1107	.5132	.4867	14.20	1.81
	5-8	1.1230	.2960	12.410	29.0	.1074	.1186	.7054	.2945	29.70	2.39
	6-7	.7720	.5120	3.380	29.0	.1214	.1341	.3136	.6863	6.20	1.83
	6-8	.7720	.2960	7.960	29.0	.1204	.1330	.5846	.4153	21.70	2.72
	7-8	.5120	.2960	4.580	29.0	.1196	.1321	.3948	.6051	15.50	3.38
13	4-5	.4260	.2440	3.030	28.0	.1839	.2075	.4066	.5933	8.80	2.90
	4-6	.4260	.1640	7.630	28.0	.1251	.1412	.5910	.4089	16.80	2.20
	4-7	.4260	.1100	10.800	28.3	.1253	.1405	.7163	.2836	23.00	2.12
	4-8	.4260	.0563	16.880	28.5	.1198	.1338	.8466	.1533	38.50	2.28
	5-6	.2440	.1640	4.600	28.0	.0863	.0974	.3107	.6892	8.00	1.73
	5-7	.2440	.1100	7.770	28.4	.1025	.1147	.5228	.4771	14.20	1.82
	5-8	.2440	.0563	13.850	28.7	.1058	.1177	.7415	.2584	29.70	2.14
	6-7	.1640	.1100	3.170	29.0	.1259	.1391	.3065	.6934	6.20	1.95
	6-8	.1640	.0563	9.250	29.0	.1155	.1276	.6247	.3752	21.70	2.34
	7-8	.1100	.0563	6.080	29.0	.1101	.1216	.4587	.5412	15.50	2.54

FIELD TRACER DATA

JACKSON RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
14	7-8	.4180	.2480	4.520	29.0	.1154	.1275	.3803	.6196	15.50	3.42
	7-9	.4180	.1500	8.900	27.0	.1151	.1328	.6251	.3748	24.70	2.77
	7-10	.4180	.0686	11.650	26.6	.1551	.1805	.8254	.1745	37.80	3.24
	7-11	.4180	.0490	14.430	26.3	.1485	.1739	.8755	.1244	47.90	3.31
	8-9	.2480	.1500	4.380	25.0	.1147	.1383	.3951	.6048	9.20	2.10
	8-10	.2480	.0686	7.130	25.0	.1802	.2171	.7233	.2766	22.30	3.13
	8-11	.2480	.0490	9.910	25.0	.1636	.1971	.8024	.1975	32.40	3.26
	9-10	.1500	.0686	2.750	25.0	.2844	.3427	.5426	.4573	13.10	4.76
	9-11	.1500	.0490	5.530	25.0	.2023	.2437	.6733	.3266	23.20	4.19
	10-11	.0686	.0490	2.780	25.0	.1210	.1458	.2857	.7142	10.10	3.63
15	8-9	.2950	.1910	3.900	24.0	.1114	.1372	.3587	.6412	9.20	2.35
	8-10	.2950	.0825	6.530	24.4	.1951	.2381	.7249	.2750	22.30	3.42
	8-11	.2950	.0621	9.310	24.9	.1673	.2020	.7902	.2097	32.40	3.48
	8-12	.2950	.0330	14.360	25.6	.1525	.1813	.8849	.1150	47.60	3.31
	9-10	.1910	.0825	2.630	25.0	.3191	.3845	.5680	.4319	13.10	4.98
	9-11	.1910	.0621	5.410	25.5	.2076	.2475	.6708	.3291	23.20	4.28
	9-12	.1910	.0330	10.460	26.2	.1678	.1970	.8192	.1807	38.40	3.67
	10-11	.0825	.0621	2.780	26.0	.1021	.1204	.2426	.7573	10.10	3.63
	10-12	.0825	.0330	7.830	26.6	.1170	.1361	.5872	.4127	25.30	3.23
	11-12	.0621	.0330	5.050	27.0	.1251	.1444	.4540	.5459	15.20	3.00

FIELD TRACER DATA

JACKSON RIVER

Dump No.	Reach	Observed Kr:H Ratio Upstr	Observed Kr:H Ratio Dnstr	Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C lost	% Tracer Gas 25°C rem	WS Elev Chnge ft	WS Elev Chnge ft/hr
16	10-11	.3060	.2310	2.420	25.0	.1161	.1399	.2450	.7549	10.10	4.17
	10-12	.3060	.1250	7.300	25.0	.1226	.1477	.5915	.4084	25.30	3.47
	10-13	.3060	.0661	9.950	25.3	.1540	.1843	.7818	.2181	35.90	3.61
	10-14	.3060	.0451	13.480	25.7	.1420	.1685	.8482	.1517	45.10	3.35
	11-12	.2310	.1250	4.880	25.0	.1258	.1516	.4588	.5411	15.20	3.11
	11-13	.2310	.0661	7.530	25.4	.1661	.1984	.7107	.2892	25.80	3.42
	11-14	.2310	.0451	11.060	25.9	.1476	.1744	.7984	.2015	35.00	3.16
	12-13	.1250	.0661	2.650	26.0	.2404	.2834	.4638	.5361	10.60	4.00
	12-14	.1250	.0451	6.180	26.6	.1649	.1919	.6263	.3736	19.80	3.20
	13-14	.0661	.0451	3.530	27.0	.1082	.1249	.3065	.6934	9.20	2.60
17	11-12	.2900	.1420	4.780	24.0	.1493	.1839	.5179	.4820	15.20	3.17
	11-13	.2900	.0828	7.900	24.0	.1586	.1953	.7222	.2777	25.80	3.26
	11-14	.2900	.0481	11.520	24.3	.1559	.1907	.8386	.1613	35.00	3.03
	11-15	.2900	.0346	15.250	25.0	.1394	.1679	.8806	.1193	45.10	2.95
	12-13	.1420	.0828	3.120	24.0	.1728	.2128	.4237	.5762	10.60	3.39
	12-14	.1420	.0481	6.740	24.5	.1606	.1956	.6652	.3347	19.80	2.93
	12-15	.1420	.0346	10.470	25.4	.1348	.1610	.7533	.2466	29.90	2.85
	13-14	.0828	.0481	3.620	25.0	.1500	.1807	.4190	.5809	9.20	2.54
	13-15	.0828	.0346	7.350	26.0	.1187	.1399	.5742	.4257	19.30	2.62
	14-15	.0481	.0346	3.730	27.0	.0883	.1018	.2705	.7294	10.10	2.70

FIELD TRACER DATA

CHATTAHOOCHEE RIVER

Dump No.	Reach	Observed Kr:H Ratio		Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C		WS Elev Chnge	
		Upstr	Dnstr					lost	rem	ft	ft/hr
XVI	0-2	.6507	.4714	5.060	25.1	.0637	.0765	.2750	.7249	6.53	1.29
XVII	2-3	.3336	.2804	3.300	20.2	.0526	.0704	.1753	.8246	3.80	1.15
	2-4	.3336	.2825	5.330	20.3	.0311	.0416	.1682	.8317	6.53	1.22
	3-4	.2804	.2825	2.030	20.5	-.0036	-.0048	-.0082	1.0082	2.73	1.34
XIX	0-2	.8958	.5956	4.930	25.0	.0827	.0997	.3351	.6648	6.69	1.35
	0-3	.8958	.5083	8.730	25.6	.0649	.0771	.4283	.5716	10.46	1.19
	2-3	.5956	.5083	3.800	26.3	.0417	.0488	.1427	.8572	3.77	.99
XX	0-2	1.0495	.8867	5.440	27.0	.0309	.0357	.1490	.8509	7.24	1.33
	0-3	1.0495	.8515	9.320	27.4	.0224	.0256	.1799	.8200	10.63	1.14
	2-3	.8867	.8515	3.880	28.0	.0104	.0117	.0372	.9627	3.39	.87
XXI	3-4	.4446	.3975	1.650	25.2	.0678	.0814	.1055	.8944	2.73	1.65
	3-5	.4446	.3699	5.010	25.4	.0367	.0438	.1666	.8333	5.57	1.11
	4-5	.3975	.3699	3.360	25.5	.0214	.0255	.0687	.9312	2.84	.84
XXII	3-4	.7214	.7193	1.760	21.5	.0016	.0021	.0031	.9968	2.70	1.53
	3-5	.7214	.6490	5.180	21.7	.0204	.0264	.1074	.8925	5.59	1.07
	3-6	.7214	.6432	7.580	22.0	.0151	.0194	.1152	.8847	6.28	.82
	4-5	.7193	.6490	3.420	21.8	.0300	.0388	.1044	.8955	2.89	.84
	4-6	.7193	.6432	5.820	22.1	.0192	.0246	.1122	.8877	3.58	.61
	5-6	.6490	.6432	2.400	22.5	.0037	.0047	.0094	.9905	.69	.28

FIELD TRACER DATA

CHATTAHOOCHEE RIVER

Dump No.	Reach	Observed Kr:H Ratio Upstr	Observed Kr:H Ratio Dnstr	Flow Time hrs	River Temp. °C	K_{kr} River Temp	K_{ox} 25°C	% Tracer Gas 25°C lost	% Tracer Gas 25°C rem	WS Elev Chnge ft	WS Elev Chnge ft/hr
XXIII	2-3	.7954	.7173	3.270	22.7	.0316	.0400	.1029	.8970	3.80	1.16
	2-4	.7954	.6230	5.390	22.7	.0453	.0574	.2265	.7734	6.62	1.22
	2-5	.7954	.5663	9.450	23.1	.0359	.0451	.2981	.7018	9.47	1.00
	3-4	.7173	.6230	2.120	22.8	.0664	.0840	.1374	.8625	2.82	1.33
	3-5	.7173	.5663	6.180	23.3	.0382	.0478	.2175	.7824	5.67	.91
	4-5	.6230	.5663	4.060	23.5	.0235	.0292	.0938	.9061	2.85	.70
XXIV	3-4	.4813	.4509	1.700	22.0	.0383	.0493	.0672	.9327	2.62	1.54
	3-5	.4813	.4089	5.190	22.5	.0314	.0399	.1581	.8418	5.56	1.07
	3-6	.4813	.3867	7.340	22.6	.0298	.0378	.2059	.7940	6.77	.92
	4-5	.4509	.4089	3.490	22.7	.0280	.0354	.0976	.9023	2.94	.84
	4-6	.4509	.3867	5.640	22.8	.0272	.0344	.1488	.8511	4.15	.73
	5-6	.4089	.3867	2.150	23.0	.0259	.0326	.0566	.9433	1.21	.56
XXV	0-2	.5930	.5578	3.430	9.7	.0178	.0299	.0818	.9181	7.73	2.25
	0-4	.5930	.4947	7.530	9.9	.0240	.0402	.2225	.7774	13.25	1.75
	0-5	.5930	.4617	10.080	9.9	.0248	.0415	.2936	.7063	17.79	1.76
	2-4	.5578	.4947	4.100	10.0	.0292	.0488	.1532	.8467	5.52	1.34
	2-5	.5578	.4617	6.650	10.0	.0284	.0474	.2305	.7694	10.06	1.51
	4-5	.4947	.4617	2.550	10.0	.0270	.0452	.0912	.9087	4.54	1.78

☆U.S. GOVERNMENT PRINTING OFFICE:1972 514-149/76 1-3

1 Accession Number

2 Subject Field & Group
05F, 05C

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

5 Organization
Georgia Institute of Technology
Atlanta, Georgia

6 Title CHARACTERIZATION OF STREAM REAERATION CAPACITY

10 Author(s)
Tsivoglou, E. C.
Wallace, J. R.

16 Project Designation
Project 16050 EDT

21 Note

22 Citation
Environmental Protection Agency report
number EPA-R3-72-012, October, 1972.

23 Descriptors (Starred First)
*Reaeration, *Streams, *Stream Pollution, *Streamflow Hydraulics, *Tracers, *Radioisotopes, *Dissolved Oxygen

25 Identifiers (Starred First)
*Stream Self-Purification, *Flint River, *South River, *Patuxent River, *Jackson River, *Chattahoochee River, *Turbulence, *Mixing, *Gas Transfer, *Stream Hydraulic Properties

27 Abstract The purposes of this research have been to characterize stream reaeration capacity in terms of the stream hydraulic properties and to develop procedures for evaluating the effects of pollutants on reaeration. Field studies of the reaeration capacity and the associated hydraulic properties of five rivers have been completed, using a gaseous tracer procedure for field measurement of reaeration. These studies have incorporated a wide range of hydraulic features, such as waterfalls, rapids, shoals and pools, with stream flows ranging from 5 to 3,000 cfs. The range of BOD's and temperatures encountered was also large. Studies of the effects of both pure substances and community wastes on the reaeration capacity have been conducted in a newly designed test system. Tests of observed vs. predicted values of K_2 have shown that none of the available models, e.g., O'Connor, Churchill, etc., is capable of providing dependable predictions of stream reaeration capacity, especially under highly turbulent flow conditions. A new energy dissipation model has been derived, by which the reaeration capacity of a stream is explained in terms of the rate of energy dissipation, measured as the loss of water surface elevation divided by the time of flow. Two distinct forms of the energy dissipation model have been tested against the observed results, and it has been shown that both forms provide dependable predictions of stream reaeration capacity. The tests of pollutant effects have shown that LAS and community wastes decrease the reaeration rate coefficient, pure NTA has no effect, and pure mineral oil increases the reaeration rate coefficient. (Tsivoglou-Georgia Tech)

Abstractor E. C. Tsivoglou

Institution Georgia Institute of Technology

WR 102 (REV JULY 1969)
WRSIC

SEND TO: WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

● GPO: 1969-359-339